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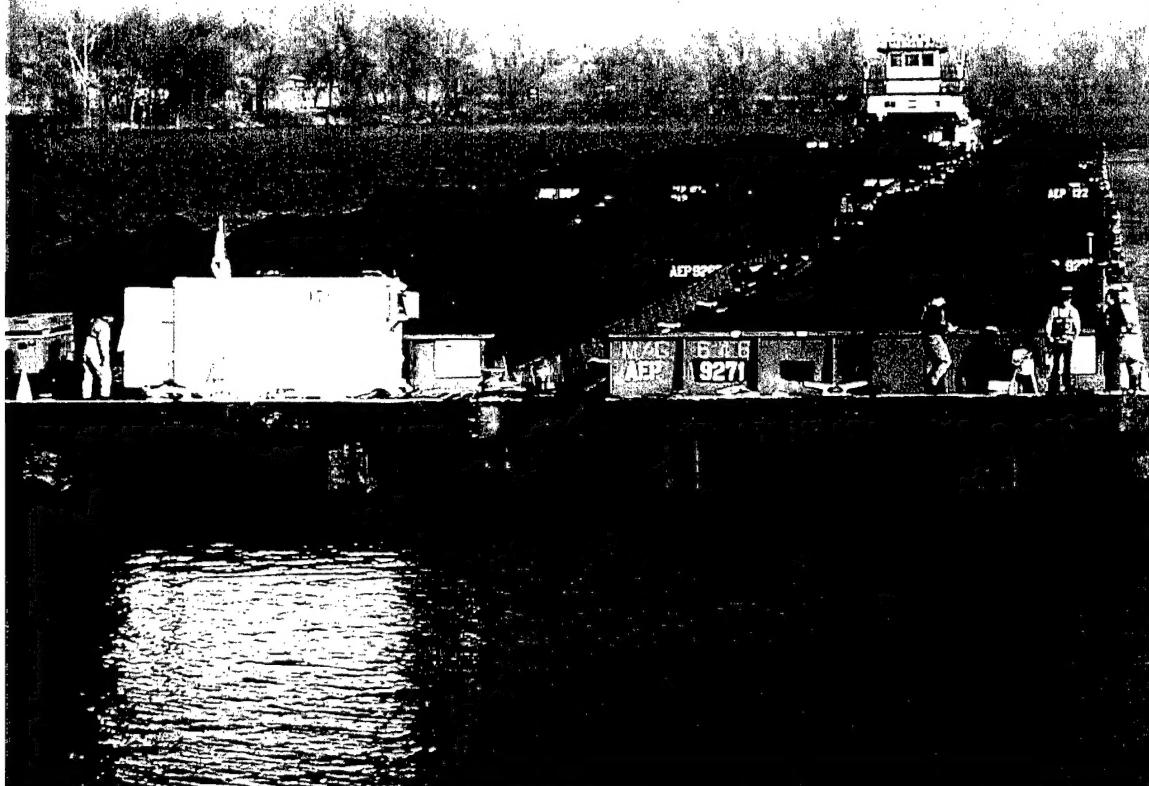
Multiple-Criteria Decision-Making in the Design of Innovative Lock Walls for Barge Impact; Phase 1

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Contents

Preface

The work described in this report was authorized by Headquarters, U.S. Army Corps of Engineers (HQUSACE), as part of the Innovations for Navigation Projects (INP) Research Program. The study was conducted under INP Work Unit 33143, "Design of Innovative Lock Walls for Barge Impact Loads." This research was initiated by Mr. Robert C. Patev, former Principal Investigator of WU 33143. Current Principal Investigator is Dr. Robert M. Ebeling of the U.S. Army Engineer Research and Development Center (ERDC) Information Technology Laboratory (ITL).

Dr. Tony C. Liu was the INP Coordinator at the Directorate of Research and Development, HQUSACE; Research Area Manager was Mr. Barry Holliday, HQUSACE; and Program Monitor was Mr. Mike Kidby, HQUSACE. Mr. William H. McAnally of the U.S. Army Engineer Research and Development Center (ERDC) Coastal and Hydraulics Laboratory was the Lead Technical Director for Navigation Systems. Dr. Stanley C. Woodson, ERDC Geotechnical and Structures Laboratory, was the INP Program Manager.

This research was performed and the report prepared by Dr. James H. Lambert, Dr. Yacov Y. Haimes, Mr. Joshua L. Tsang, and Mr. Paul Jiang of the Center for Risk Management of Engineering Systems, University of Virginia, Charlottesville, and Mr. Patev, currently of the U.S. Army Engineer District, New England, Concord, MA.

The research was monitored by Dr. Ebeling, under the supervision of Mr. H. Wayne Jones, Chief, Computer-Aided Engineering Division, ITL; Mr. Tim Ables, Acting Director, ITL; and Dr. Michael J. O'Connor, Director, GSL.

At the time of publication of this report, Dr. James R. Houston was Director of ERDC, and COL John W. Morris III, EN, was Commander and Executive Director.

1 Introduction

1.1 Background

Currently, the design of U.S. Army Corps of Engineers (USACE) navigation structures involves considering the combination of possible extreme events such as barge-impact forces and earthquake loading. Designing to such arbitrary extreme events can result in substantial increases in the final design and construction costs. However, with the trend toward thinner, more economical structures using innovative design and construction techniques, the existing design criteria and decision-making process should be re-examined in detail to ensure the viability, including safety and cost-effectiveness, of such designs.

The USACE has tried to establish criteria for lock wall design that consider barge-impact forces and earthquake loads for various return-period scenarios (for example, a usual or 1-year return; an unusual or 500-year return; and an extreme or 1,000-year return). Typically, depending upon the impacts of the worst-case scenario on the safety and economic development of the structure's future, the design favors the larger return periods, leading to higher construction costs.

The current phase of the investigation reported herein involves the development of a process to aid the USACE in seeking an appropriate balance among the risks of multiple-impact hazards and present and future costs for the design of innovative lock walls. The process is grounded in existing models for the failure modes of the lock walls, multiple-criteria decision-making theory and methodology, and the assessment and management of risk of extreme events.

This report is organized as follows: the section below summarizes a review of the current state of knowledge with regard to the design of navigation locks. Chapter 2 explains the concepts of multiple-criteria decision-making and its theory, and Chapter 3 explains the conceptual framework developed for considering multiple hazards to lock structures, and the tradeoffs that could be made in deciding among different designs. In Chapter 4, the reliability and mean time to failure due to multiple failure modes for navigation structures is discussed. Finally, Chapter 5 details the management of risk and outlines how compound modes of failure could be addressed. Appendixes to this report provide a "generic" example problem showing how the methodology developed in Phase 1 applies to the evaluation of navigation locks (Appendix A) and the mathematical details for partial failure modes (Appendix B).

1.2   Review of Literature

The economic life of a typical navigation dam and lock project is thought to be 50 years. Once the planners establish the project's economic life, they need to decide on the structure's protection, which must meet some minimum acceptable design-level criterion. Traditionally, these design levels have been specified in engineering standards, such as ASCE Standard 7-88 (1990). The standards specify appropriate nominal load values and combinations of loads to be used in design. Ellingwood (1995) gives the formulas from these standards to calculate the design load values. Ellingwood (1995) provides the mathematical basis for event-combination analysis but does not show tradeoffs between costs and risks among different design combinations. The combinations of design events, $X_i(t)$, can be represented by

$$U(t) = X_1(t) + X_2(t) + \ldots + X_n(t) \tag{1}$$

where $U(t)$ represents a combination of structural load effects due to operational and environmental events that occur randomly. The maximum of the combined load effects, U_{max}, in a given time interval $0 \le t \le T$ is expressed as

$$U_{max} = \max U(t) \tag{2}$$
$$0 \le t \le T$$

There are two primary methods for event-combination analysis: load-crossing (upcrossing) analysis and load-coincidence analysis. The first method is used to calculate the frequency of a load that exceeds some critical level. The second method accounts for the timing of occurrences for different loads, which the upcrossing type of analysis does not consider.

Ellingwood (1995) discusses different types of loading conditions—dead, snow, wind, earthquake, flood, operating, and barge-impact loads—and explains the commonly used models for assessing these loads on an individual basis. An example event-combination analysis is performed using the load-coincidence method to find the probabilities of two different load events occurring together at a particular facility. The pairs of events considered include operating loads and wind, operating loads and earthquake, operating loads and barge impact, earthquake and barge impact, and earthquake and flood. For the particular facility, only the coincidence probabilities for operating loads and earthquake and for earthquake and barge impact appear significant enough to warrant additional possible development of design load combinations. The results are site specific, however, and other facilities should be studied before making any final conclusions.

The USACE Huntington District has commissioned studies for the design of barge-impact loads for the lock walls at Marmet Lock and Dam (Patev 2000) and the design of the lock walls at the Winfield Lock and Dam (Glosten & Associates 1995). Patev and Glosten both calculate the maximum impact loads associated with specific return periods. The method used for calculating impact loads is based on the methodology contained in Patev (1999). Although only the usual, unusual, and extreme loading conditions are presented in the final results, the

analysis is probabilistically based. Therefore, both analyses are able to support the current effort of developing tradeoff analyses.

For a range of potential impact loads, Patev and Glosten calculate the probabilities that a collision with an impact exceeding a certain level will occur at a landing in any given year during the life of the project. To calculate the maximum impact load results from scale model, experiments are required to determine impact velocities and angles for a tow. The mass and dimensions of barge tows and their per-event probabilities are also needed, as well as the life-of-project forecast utilization for the number of lockages per year. In addition, this study shows the currently used metrics for quantifying risks of barge impacts to navigation structures. The metrics are the probability of a barge impact exceeding a set level, namely these: the per-event, the annualized, and the life-of-project exceedance probability and the return period. As is well known, the return period in years is equal to one divided by the annualized exceedance probability. Table 1 shows the metrics considered in these two sources.

Table 1
Definitions of Risk Metrics Used by the Corps of Engineers

Metric	Definition
Per-event exceedance probability	Probability *for each landing* that the impact-force level exceeds a specified value
Annualized exceedance probability	Probability that the maximum impact force in *any one year* exceeds a specified value
Life-of-project exceedance probability	Probability that the maximum impact force in *M years* exceeds a specified value
Return period	The average number of years between occurrences of a collision with a particular impact load
Annualized probability that maximum force is less than a set level	Probability that the maximum impact force in *any one year* is below a specified value

To see the tradeoffs between costs and risks of different lock designs, one needs to identify relevant costs. Several reports available from the Corps' Web sites have been reviewed for metrics for costs associated with navigation locks. Some of the reports were checked for metrics for risks and damage. Metrics for costs are shown in Table 2. There is some overlapping, in that some metrics are more detailed breakdowns of costs, while others (such as those for life-cycle projects) are total costs.

Table 2	
Cost Metrics	
Cost Metric	Reference
Annualized initial	ER 1110-2-1404
Annualized installation	ER 1110-2-1404, ER 1105-2-100
Annualized operational	ER 1110-2-1404
Annualized maintenance	ER 1110-2-1404
Annualized repair	ER 1105-2-100, ER 1110-2-1404, and ER 1110-2-1457
Annualized rehabilitation	ER 1110-2-1404
Annualized replacement	ER 1110-2-1404
Operational (over a period of analysis)	ER 1105-2-100
Maintenance	ER 1105-2-100
Repair	ER 1105-2-100
Baseline estimate/Total current working estimate Fully funded project cost; includes lands and damages, construction features (labor, equipment, and materials), planning, engineering, design, and supervision, administration with appropriate contingencies, and escalation associated with each of these activities through project completion.	ER 1110-2-1150, ER 1110-2-1302
Civil works breakdown structure—All costs throughout the project life cycle: Lands and damages Relocations Reservoirs Dams Locks Fish and wildlife facilities Power plant Roads, railroads, and bridges Channels and canals Breakwaters and seawalls Levees and floodwalls Navigation ports and harbors Pumping plants Recreation facilities Flood control and diversion structures Bank stabilization Beach replenishment Cultural resource preservation Buildings, grounds, and utilities Permanent operating equipment Reconnaissance studies, feasibility studies, planning, engineering, and design Construction management	ER 1110-2-1302
Annual project cost	EM 1110-2-1615, EM 1110-2-2904
Aids to navigation (for small-boat navigation projects)	EM 1110-2-1615
Life-cycle project cost (50 years for small-boat navigation projects)	EM 1110-2-1615
Direct labor	EP 37-1-3
Direct costs	EP 37-1-3
Indirect costs	EP 37-1-3
Real estate — buying land for a project	ER 1105-2-100
Benefits (decrease in losses of time and property due to failure of structure)	ASCE 1998

The relationships between a design's protection level and its various costs are not straightforward. Though construction cost increases with heightening of the protection level, maintenance, replacement, and present-worth annual costs decrease. Also, the potential benefits (decreases in losses of time and property due to a shutdown) are greater for a sturdier structure (ASCE 1998). Clearly, there are tradeoffs the USACE must make in deciding between designs of different protection levels.

Table 3 shows the metrics for risks employed by the Corps.

Table 3 Risk Metrics and Reference Documents	
Risk Metric	**Reference**
Mean time to failure	ETL 1110-2-549
Mean number of failures over a specified amount of time	ETL 1110-2-549
Probability of exceedance of ground motion	EM 1110-2-6050
Usual, unusual, and extreme load conditions with associated annual probabilities of exceedance	Patev (2000)
Design forces for 1-, 10-, 100-, and 1,000-year events	Patev (2000)
Allowable stress	
Safety factor	
Per-event exceedance probability	Patev (2000), Glosten & Associates (1995)
Annualized exceedance probability	Patev (2000), Glosten & Associates (1995)
Life-of-project exceedance probability	Patev (2000), Glosten & Associates (1995)
Return period impact force	Patev (2000), Glosten & Associates (1995)
Annualized probability that maximum force is less than a set level	
Cost of lost business due to failure of locks	

2 Concepts and Theory of Multiple-Criteria Decision-Making

The tradeoffs among multiple noncommensurate and often conflicting and competing objectives are at the heart of risk management. One is invariably faced with deciding the level of safety (the level of risk that is deemed acceptable) and the acceptable cost associated with that safety. The following student dilemma is used to demonstrate the fundamental concepts of Pareto optimality and tradeoffs in a multi-objective framework (Chankong and Haimes 1983).

A student working part-time to support her college education is faced with the following dilemma that is familiar to all of us:

$$Maximize \begin{cases} \text{income} \\ \text{grade-point} \\ \text{leisure} \end{cases}$$

In order to use the two-dimensional plane for graphic purposes, we will restrict our discussion to two objectives: maximize income and maximize grade-point average (GPA). We will assume that a total of 70 hr per week are allocated for studying and working. The remaining 98 hr per week are available for "leisure time," covering all other activities. Figure 1 depicts the income generated per week as a function of hours of work. Figure 2 depicts the relationship between studying and GPA. Figure 3 is a dual plotting of both functions (income and GPA) versus working time and studying time.

The concept of optimality in multiple objectives differs in a fundamental way from that of a single-objective optimization. Pareto optimality in a multi-objective framework is that solution, policy, or option for which one can improve one objective function only at the expense of degrading another. A Pareto optimal solution is also known as a noninferior, nondominated, or efficient solution. In Figure 1, for example, studying up to 60 hr per week (and correspondingly working 10 hr per week) is Pareto optimal, since in this range, income is sacrificed for a higher GPA. On the other hand, studying over 60 hr per week (or working less than 10 hr per week) is a non-Pareto optimal policy, since in this range both income and GPA are diminishing. A non-Pareto optimal solution is also known as an inferior, dominated, or nonefficient solution.
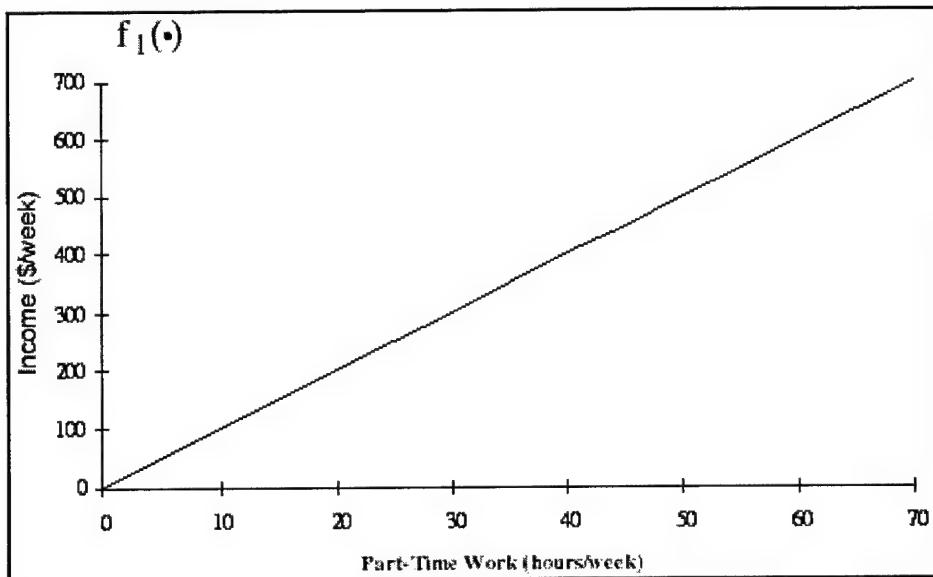
Figure 1. Income from part-time work
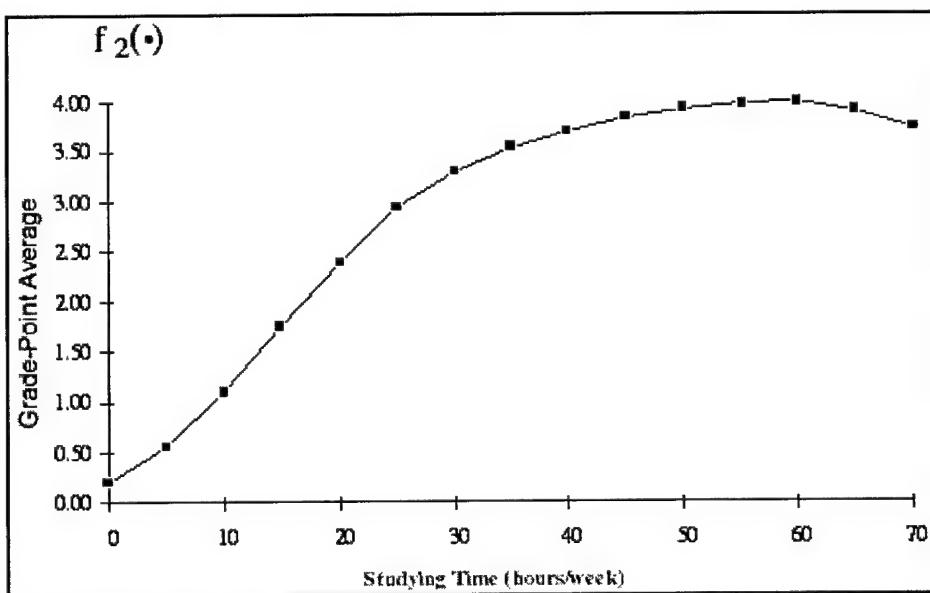
Figure 2. GPA as a function of studying time

Figure 4 further distinguishes between Pareto and non-Pareto optimal solutions by plotting income versus GPA. The line connecting all the square points is called the Pareto optimal frontier. Note that any point interior to this frontier is non-Pareto optimal. Consider, for example, policy option A. At this point the student makes $300 per week at a GPA of just above 1, whereas at point B she makes $600 per week at the same GPA level. One can easily show that all points (policy options) interior to the Pareto optimal frontier are inferior points.
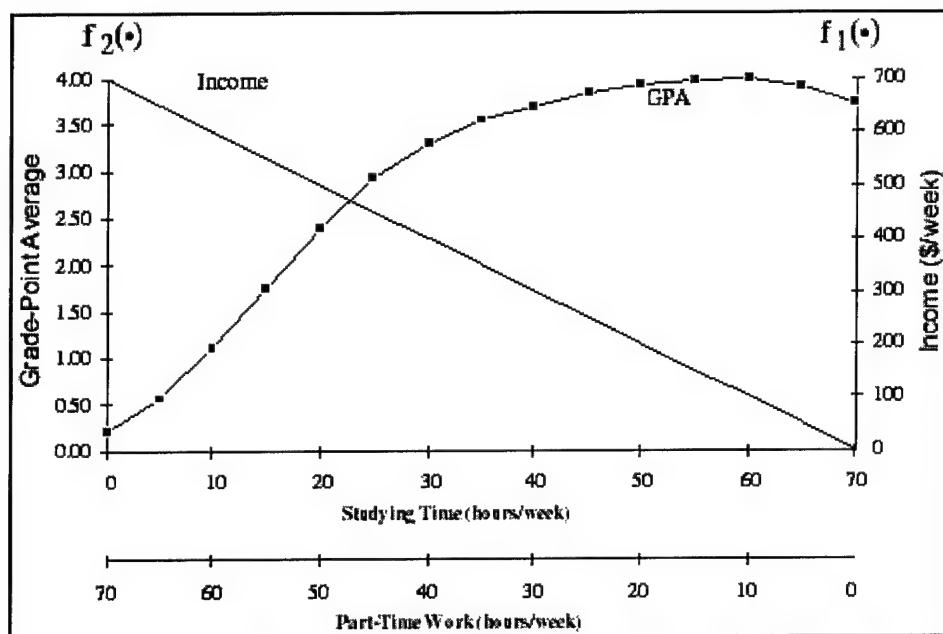
Figure 3. GPA versus income
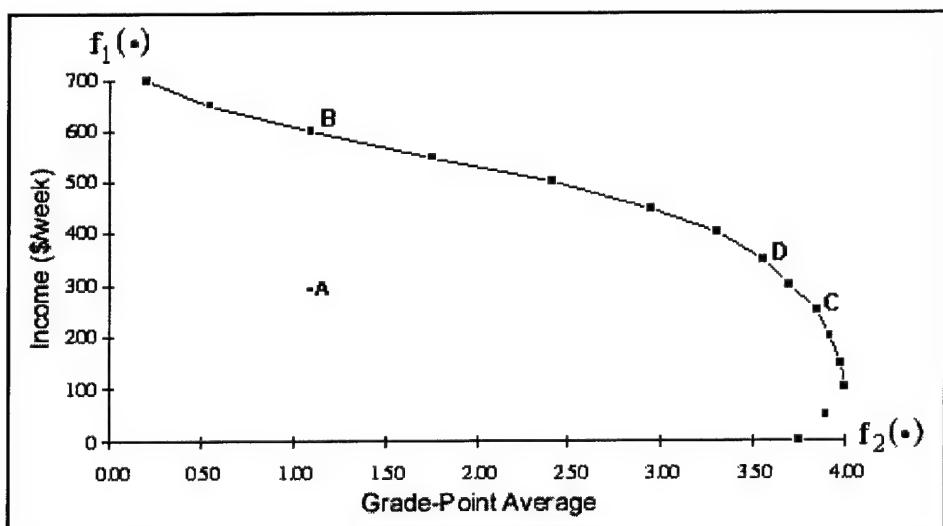
Figure 4. Pareto optimal frontier

Consider the risk of groundwater contamination as another example. We can generate the Pareto optimal frontier for this risk-based decision-making. Minimizing the cost of contamination prevention and the risk of contamination is similar in many ways to generating the Pareto optimal frontier for the student dilemma problem. Determining the best work-study policy for the student can be compared to determining the level of safety, that is, the level of acceptability of risk of contamination and the cost associated with the prevention of such contamination.

To arrive at this level of acceptable risk, we will again refer to the student dilemma problem illustrated in Figure 4. At point B the student is making about

$600 per week at a GPA of just above 1. Note that the slope at this point is about $100 per week for each 1 GPA. Thus, the student will opt to study more. At point C, the student can achieve a GPA of about 3.6 and a weekly income of about $250. The tradeoff (slope) at this point is very large. By sacrificing about 0.2 GPA the student can increase her income by about $200 per week. Obviously, the student may choose neither policy B nor C; rather she may settle for something like policy D, with an acceptable level of income and GPA. In a similar way, and short of strict regulatory requirements, a decision-maker may determine how much of available resources to allocate for the prevention of groundwater contamination at an acceptable level of risk of contamination.

In summary, the question is, Why should we expect environmental or other technologically based problems involving risk-cost-benefit tradeoffs to be any easier than solving the student dilemma?

A single decision-maker as in the student dilemma problem is not common, especially when dealing with public policy; rather, the existence of multiple decision-makers is more prevalent. Indeed, policy options on important and encompassing issues are rarely formulated, traded-off, evaluated, and finally decided upon at one single level in the hierarchical decision-making process. Rather, a hierarchy that represents various constituencies, stakeholders, power brokers, advisors, administrators, and a host of "shakers and movers" constitutes the true players in the complex decision-making process. For more on multi-objective analysis, see Haimes and Hall (1974), Chankong and Haimes (1983), and Haimes, Moser, and Stakhiv (1994).

3   Hazard Analysis

Several design events can cause failure of a lock approach structure, including barge impact, earthquake, operator error, and the extreme event of bombing by terrorists. In the current study efforts, the focus is primarily on the impact of collisions (i.e., barge impacts) and earthquakes. This chapter addresses these two failure modes separately. Chapter 4 examines the possible effects and combination of these two failure modes jointly.

3.1   Barge Impact

There is a growing body of literature devoted to the study of barge impact on lock walls. Patev (2000) proposed a computational framework termed *Probabilistic Barge Impact Analysis* (PBIA) for Marmet Locks and Dam. This framework is geared toward calculating the barge-impact load, provided that probabilistic information about the size and mass of the barge, the impact velocity, and the impact angles is relatively known (Patev 1999). Patev (2000) performed a detailed study on the upper guide and guard walls at Marmet Locks and Dam based on the PBIA. Glosten & Associates (1995) presented a study on barge-impact loads for the Winfield Lock and Dam approach guard wall. Both studies show a similar relationship between return period and impact loads. Figure 5 represents this relationship for the Winfield case.

Allowable maximum stress, a design criterion for this type of structure, is associated with the maximum impact loads the structure can endure. In general, the probability that a structure fails can be determined by (Ellingwood 1995)

$$P(F) = \sum_i P(F|E_i)\, P(E_i) \tag{3}$$

where

$P(F)$ =   overall probability of failure

$P(F|E_i)$ =   conditional probability of failure

$P(E_i)$ =   probability of event E

and the summation is carried out over all possible events. This assumes the events are statistically independent. Of primary interest in this present study is the conditional probability $P(F|E_i)$. The designed maximum impact load is
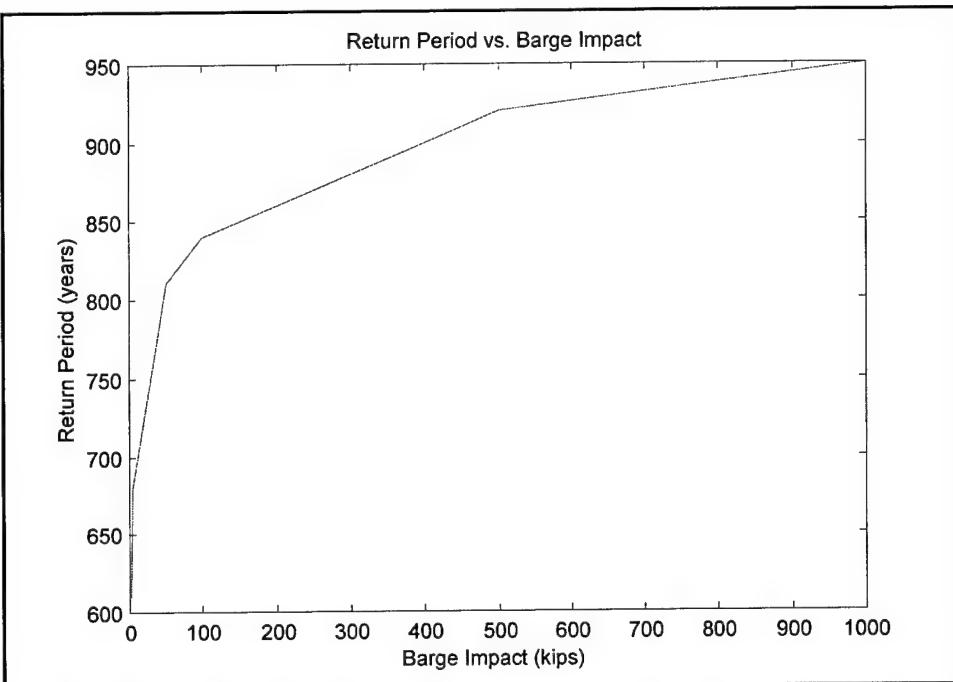
Figure 5.   Return period versus barge normal impact force – Winfield Lock
(Glosten & Associates 1995)

defined as the load that leads to $P(F|E_i) = 1$. In other words, any impact load
beyond this level will cause the structure to fail, entailing either full
reconstruction or a major repair, both of which will result in significant
construction costs. Likewise, the loads less than this level will have a $P(F|E_i)$ of
less than 1.

As a simplification, it is assumed that this type of load will cause partial
failure of the structure. From a strict probabilistic point of view, however, it
could contribute to the eventual failure of the structure as well. This issue will be
revisited in the following section to offer a probabilistic treatment. For the time
being, attention is focused on loads exceeding the Designed Maximum Impact
Load (DMIL). Given the DMIL, which Ellingwood (1995) somewhat considered,
one would like to know the mean time to failure (MTTF). If the probabilistic
distribution of the impact load is known (i.e., probability density function or pdf),
then the MTTF can be calculated via evaluating the exceedance probability at the
DMIL. The probability that an impact would exceed a certain level is shown in
Figure 6 as the area under the curve (pdf) to the right of that amount. Specifi-
cally, if the exceedance probability at the DMIL is $1/n$, each collision has a
chance of exceeding the DMIL of $1/n$. Furthermore, on average, n collisions
occur before one that exceeds the DMIL occurs. If the mean interarrival time of
collisions is $\overline{\tau}$, then the MTTF is $n\overline{\tau}$ because n collisions that occur every $\overline{\tau}$
time unit are necessary for a failure. The MTTF is the same as the return period
of the collision that has an impact magnitude equal to or greater than the DMIL.
One can find the return period by conducting a PBIA if input data are provided.
Figure 7 shows the MTTF for the Winfield Lock and Dam.
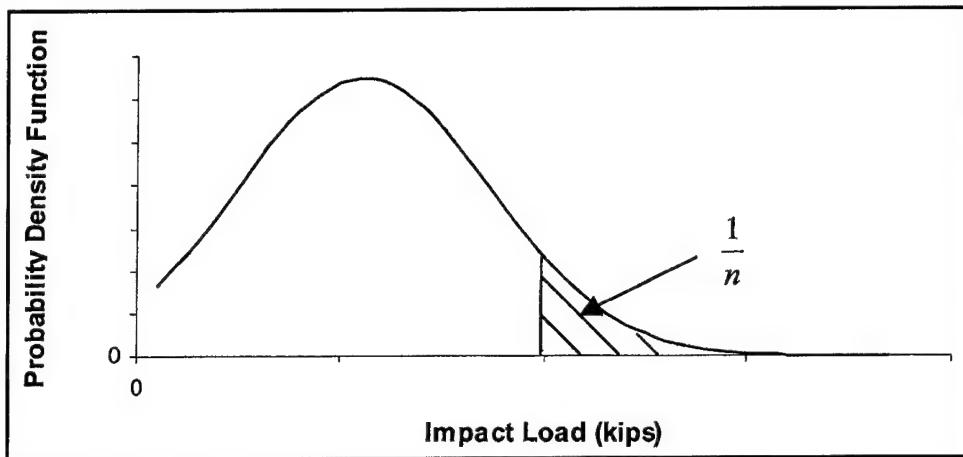
Figure 6. Probability density function of impact load
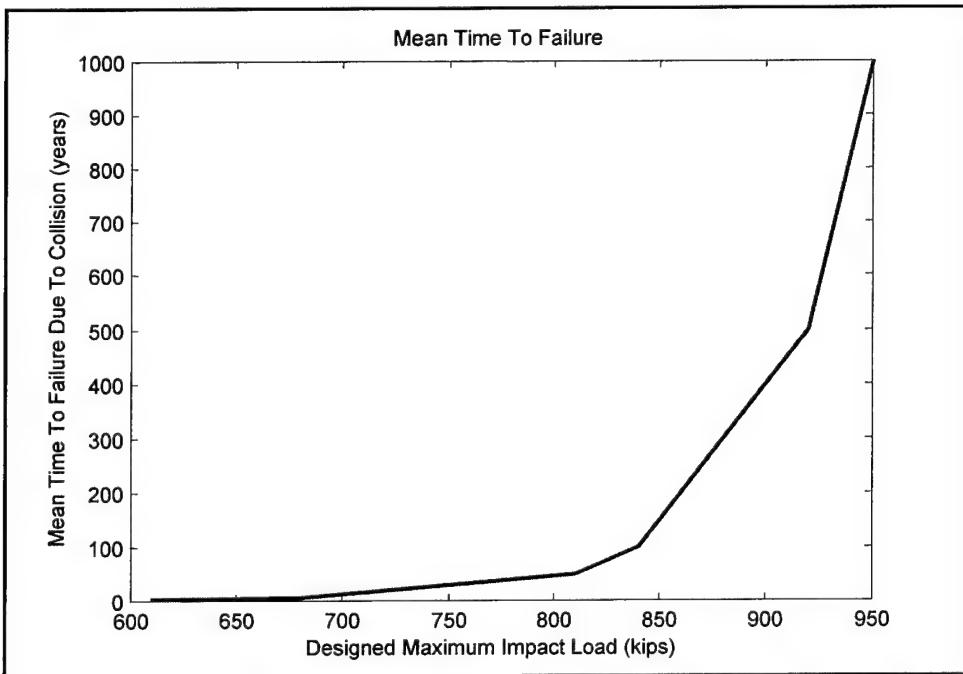
Figure 7. Mean time to failure for Winfield Lock

Apart from complete failure, one may also be concerned with other significant but less severe collisions that may call for structural repair. The severity of an impact can be defined to be the ratio of the estimated repair cost to the estimated reconstruction cost. The severity is thus typically less than or equal to 1. The exact relationship between the severity and the impact load might be determined through historical data and, in general, for any given impact, the severity may contain uncertainty (e.g., described by a range or a probability distribution). This point will be addressed in Chapter 5 as a probabilistic model for the severity. At this point, we will assume a deterministic exponential relationship between these two variables:

$$S = \frac{e^{\beta x} - 1}{e^{\beta} - 1} \qquad\qquad (4)$$

where

S = severity, ranging between 0 and 1

β = parameter to be determined from historical data

$$x = \frac{\text{Actual Impact Load}}{\text{Designed Maximum Impact Load}}$$

Figure 8 depicts the severity-impact load relationship for the cases $\hat{\beta} = 2, 5, 10$.
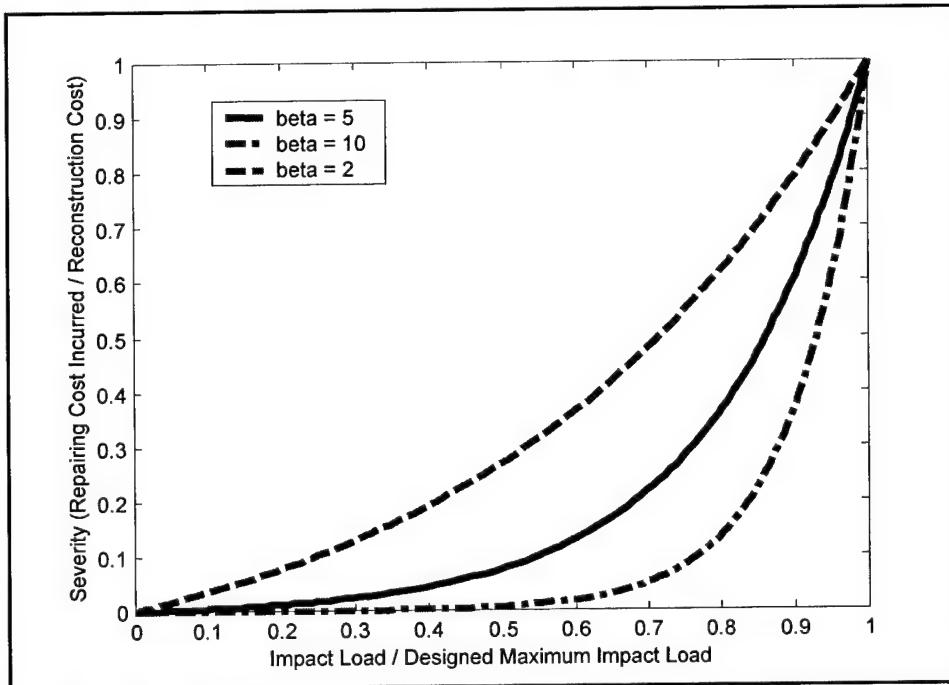
Figure 8.   Severity, β versus impact load

For the following discussion, the nominal value of β is assumed to be 5. For the sake of simplicity, only one representative line is drawn for each of the impact load cases discussed before—usual, unusual, and extreme. Figure 9 shows the relationship between the DMIL for each case and severity. The lines shown in Figure 9 indicate that a tradeoff is needed when designing the navigation structure because of the multi-objective nature of this problem.

For instance, if a relatively economical design with a designed maximum impact load of 1,000 kips (4,450 kN) is favored, then an impact with a 100-year return period will result in a damage with severity 0.47, and an impact with a 1,000-year return period will result in a damage with severity 0.78. On the other hand, if a more sturdy design is desired, such as one with a designed maximum impact load of 1,600 kips (7,120 kN), then an impact with a return period of
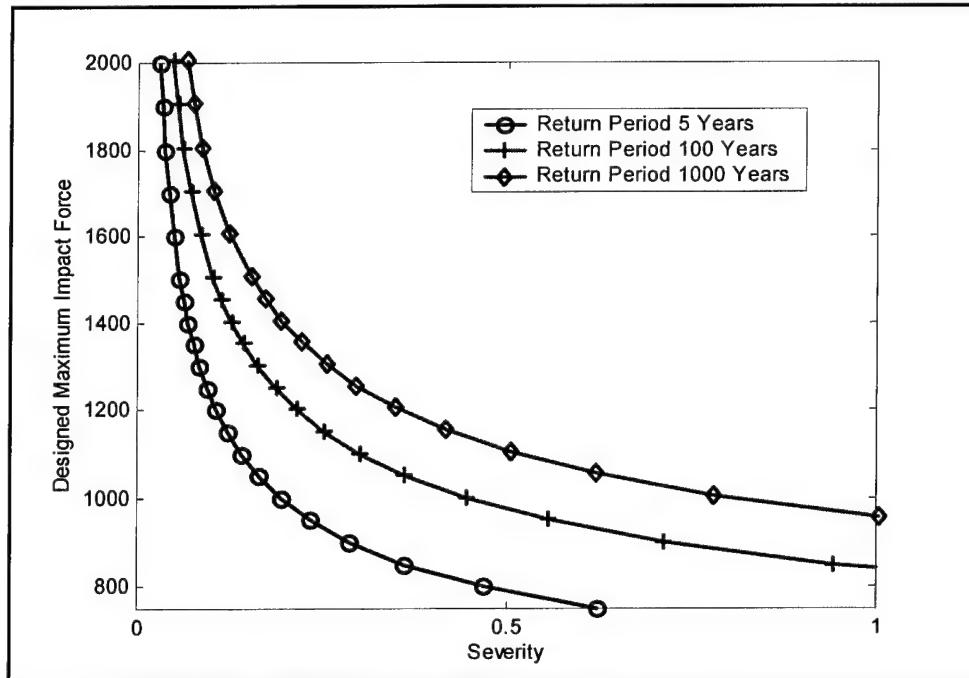
Figure 9.   Designed maximum impact force versus severity

100 years will result in a damage with severity 0.09 only, and an impact with a return period of 1,000 years will result in a damage with severity 0.127 only. Of course, such a sturdy design is expected to be much more costly. Hence, it is important to maintain a balance between cost and sturdiness. To achieve such a goal, a comprehensive tradeoff analysis is necessary (Haimes 1998).

3.2   Earthquake

A method of calculating the peak ground acceleration (PGA) and return period using probabilistic methods is termed a Probabilistic Seismic Hazard Analysis (PSHA) and is discussed in detail in Engineer Manual (EM) 1110-2-6050. This technique allows one to uncover the relationship between the level of peak ground acceleration from an earthquake and the annual frequency of exceedance of that level, provided that the relevant statistical information is available. Examples of required information for a PSHA include the following: locations of the seismic sources, annual frequency of occurrence of earthquakes of given magnitude, and probability of an earthquake of given magnitude at a site that is at a certain distance from the source. Figure 10 shows a typical hazard curve as a result of a PSHA calculation (EM 1110-2-6050).
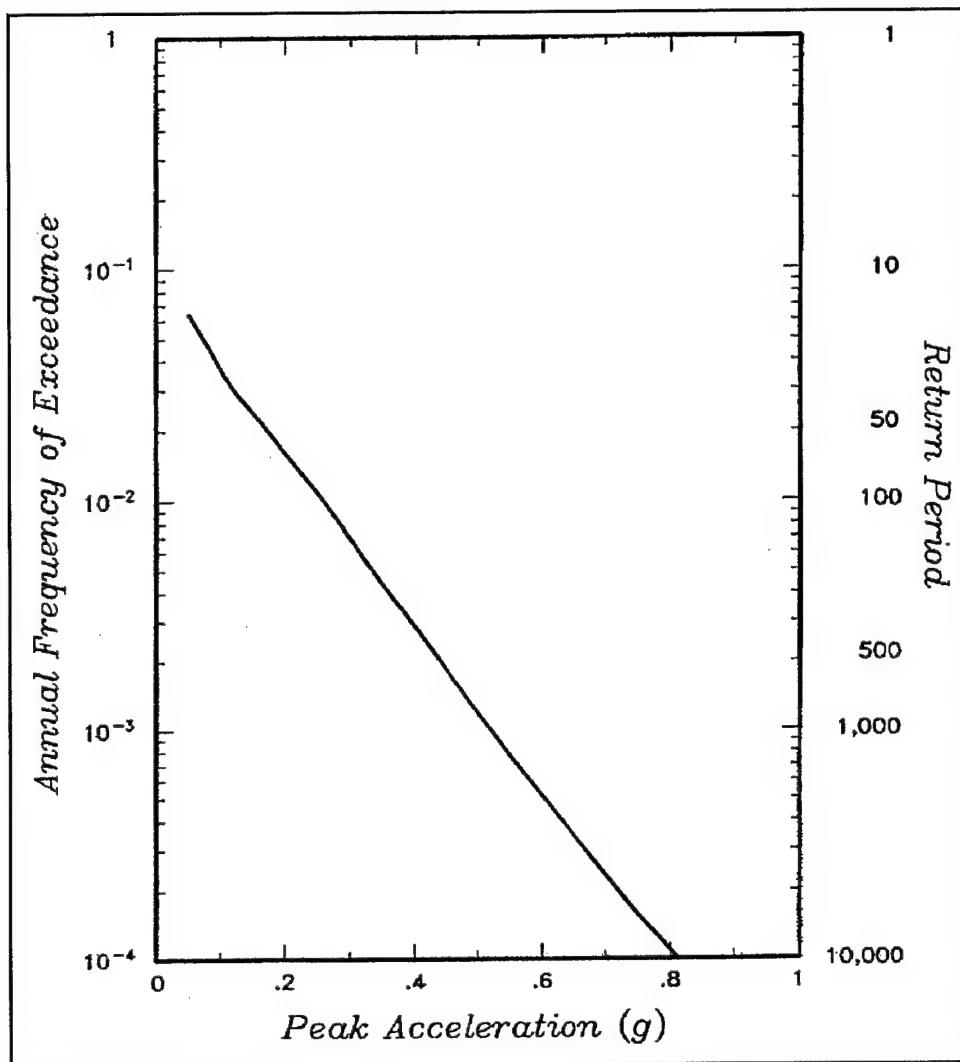
Figure 10. Hazard curve for PSHA (from EM 1110-2-6050)

Figure 10 shows that the relationship between the return period and the logarithmic value of the ground motion (i.e., PGA) is approximately a straight line. This figure suggests that, as a first-order approximation, one may assume an exponential relationship between the level of ground motion and the return period as follows:

$$T = e^{13.671a} + 66.076 \tag{5}$$

where

$\quad T$ = return period in years

$\quad a$ = peak ground acceleration evaluated in terms of the gravitational acceleration, g

The parameters for Equation 5 were estimated from the results of the PHSA shown in Figure 10.

Similar to the DMIL in the barge-impact case, another design criterion for a navigation structure should be the maximum ground motion (PGA) that the structure can withstand. In other words, the concern is with the level of ground motion beyond which the structure will fail and therefore will require a complete reconstruction. Given the Designed Maximum Ground Motion (DMGM), the MTTF due to earthquakes can be calculated. If the probabilistic distribution of the earthquake load in terms of the ground motion is known, then the MTTF can be calculated via evaluating the exceedance probability at the DMGM. Specifically, if the exceedance probability at the DMGM is $1/n$, and the mean time between earthquakes is $\bar{\tau}$, then the MTTF is $n\bar{\tau}$.

On the other hand, the quantity $n\bar{\tau}$ is nothing but the return period of the earthquake that has a resulting ground motion equal to or greater than the DMGM. Thus, the entire task of finding the MTTF comes down to finding out the return period of an earthquake of specific magnitude. This can be accomplished by performing a PSHA if all necessary information is available and provided. Figure 11 shows the MTTF for a prototypical case provided by EM 1110-2-6050.
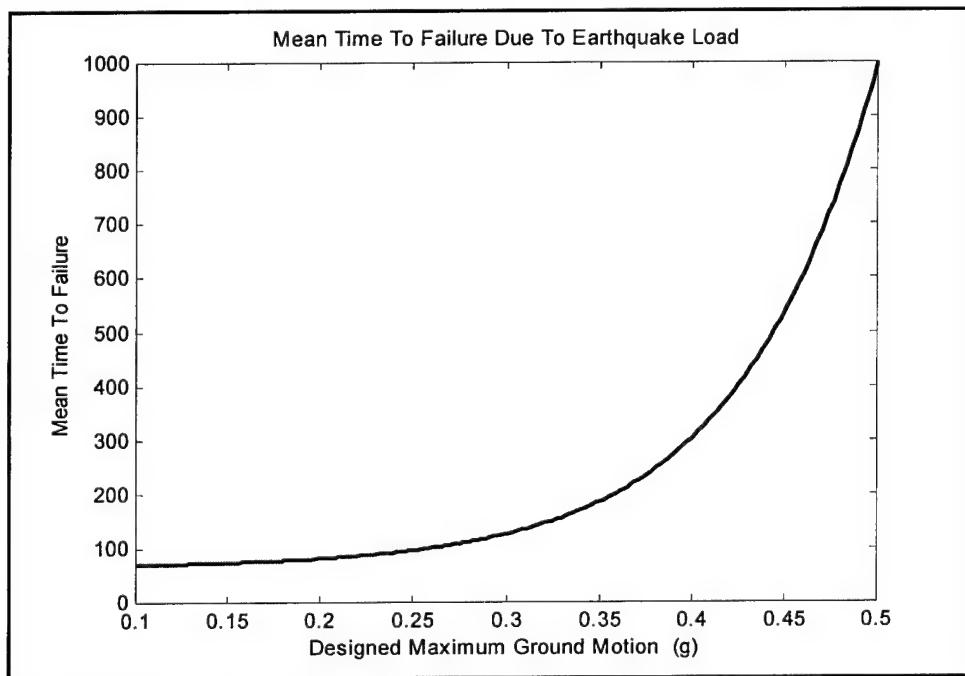
Figure 11. Mean time to failure due to earthquake load

As discussed previously, in addition to the complete failure, one should also be concerned with other significant but less severe earthquake consequences that may cause the structure to require repairs. Similar to the collision case, the severity of an earthquake impact is defined to be the ratio of the repair cost to the complete reconstruction cost. Obviously, the severity should be less than or equal to 1. The exact relationship between the severity and the ground motion should be determined using historical data and studies related to the project. In general, for any given earthquake load, the severity may be uncertain, that is, described by

a range or a probabilistic distribution (pdf). This point will be addressed further in Chapter 5.

An exponential relationship between these two variables is assumed,

$$S = \frac{e^{\beta x} - 1}{e^{\beta} - 1} \qquad (6)$$

where

β = parameter to be determined by historical data and related study

$$x = \frac{\text{Actual Ground Motion}}{\text{Designed Maximum Ground Motion}}$$

Figure 12 depicts the severity-impact load relationship for $\hat{\beta}$ = 10, 30, 40. In the following discussion and example for earthquake loads, the nominal value of β is taken as 30.
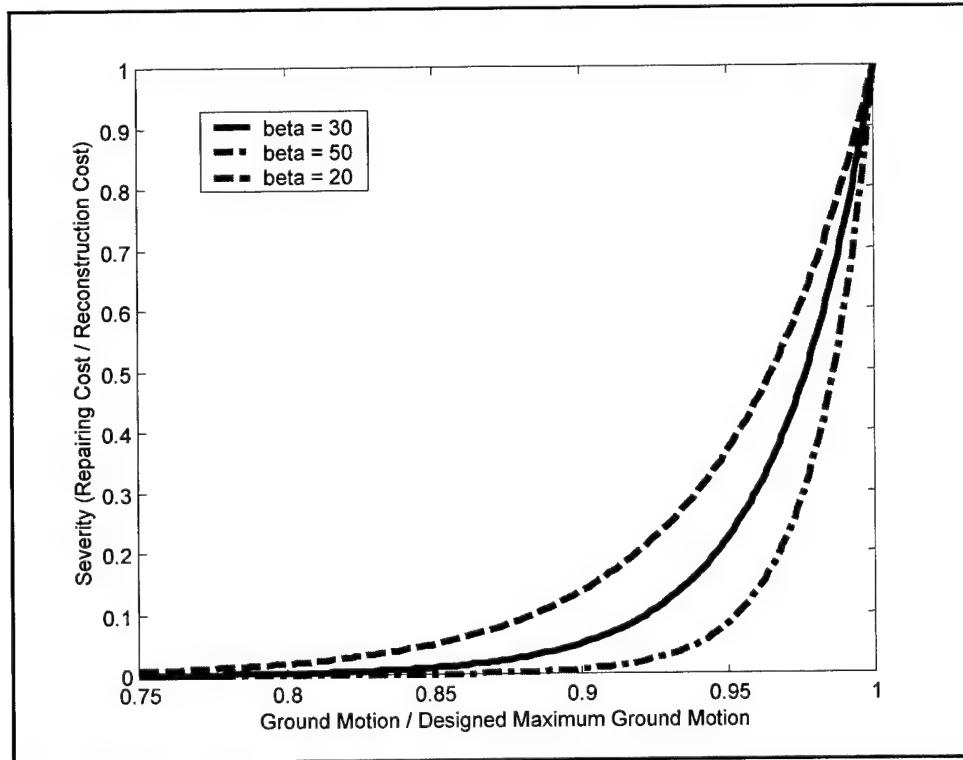
Figure 12.   Severity versus ground motion

Similar to the explanation from Figure 9 for barge impact, Figure 13 describes the relationship between the DMGM and the severity. Again, for the sake of simplicity, only one representative line is drawn for each of the load case events: usual, unusual, and extreme. These lines indicate that a tradeoff is needed when designing the navigation structure because of the multi-objective nature of the
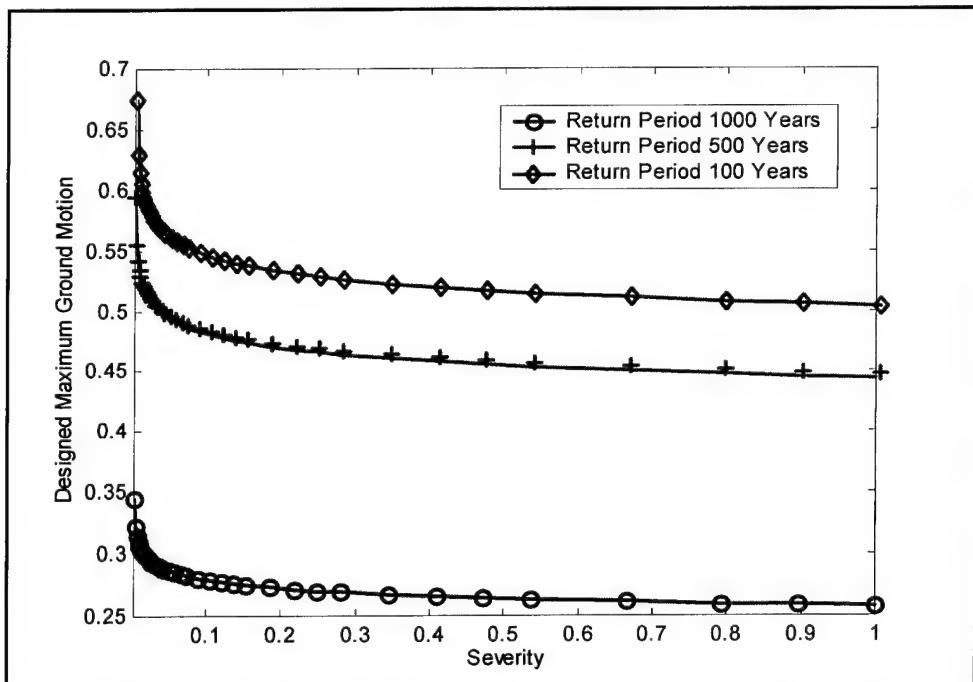
Figure 13.   Designed maximum ground motion versus severity

problem. For instance, if a relatively economical design with a designed maximum ground motion of only 0.275g is favored, then an earthquake load with 100-year return period will result in a damage severity of 0.09, while an earthquake load with a 500-year return period will completely collapse the lock structure with a severity of 1. If a more robust design with a maximum ground motion of 0.5g is desired, then an earthquake load with a return period of 100 years will have minimal effect on the structure, and an earthquake load with return period of 500 years will result in a damage with severity of 0.03 only. However, for this case, an earthquake load with a 1,000-year return period will result in complete collapse of the structure.

On the other hand, if the designed maximum ground motion is 0.55g, then an earthquake load with return period of 1,000 years will result in a damage with a severity of only 0.07. Since such a robust design is expected to be much more costly to actually implement, a rationally defined balance between cost and sturdiness needs to be maintained. To achieve such a goal, a comprehensive tradeoff analysis will be required (Haimes 1998).

4 Lock Reliability Due to Multiple Failure Modes

4.1 Basic Reliability Analysis

Before proceeding, a few important reliability concepts will be addressed (Ross 1997, Haimes 1998):

Reliability, *R(t)*: probability that the lock performs its desired function throughout the time interval $(0, t)$, given that it was operating properly at $t = 0$.

Unreliability, *Q(t)*: probability that the lock fails during a time interval $(0, t)$, given that it was operating properly at $t = 0$. Obviously, $Q(t) = 1 - R(t)$.

Failure density, *f(t)*: probability density of failure. Namely, the term $f(t)dt$ is the probability that the lock fails in the time interval $(t, t+dt)$. Mathematically,

$f(t) = dQ(t)/dt$

Failure (hazard) rate, *λ(t)*: the term $\lambda(t)\,dt$ is the conditional probability of lock failure in the time interval $(t, t+dt)$, given that no failure occurs up to time t. In other words, $\lambda(t) = f(t)/R(t)$.

Mean time to failure (MTTF), $\overline{T}$: the expected time the lock will operate properly before it fails. Mathematically,

$$\overline{T} = \int_0^\infty R(t)dt$$

In general, $R(t)$ is a monotonically decreasing function. It is important to note that the reliability function is directly tied to the level of design. A stronger design generally results in a slower decrease in reliability over time. Figure 14 shows a comparison of different design levels in terms of a generic reliability.
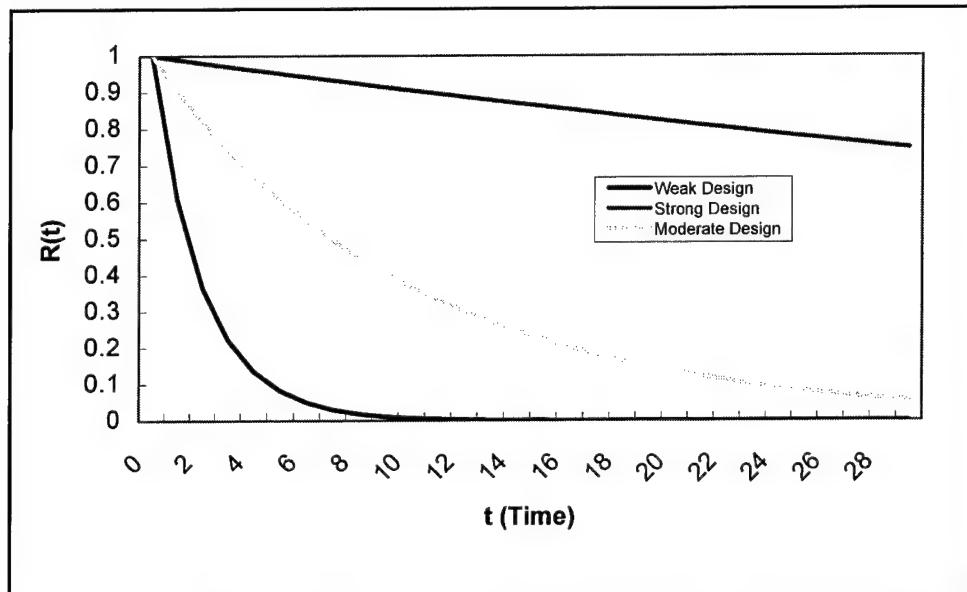
Figure 14. Reliability over time

If the probability of a barge impact whose magnitude exceeds the designed maximum impact load (DMIL) during a typical year is $1/n$, the reliability of the lock at time t is

$$R_c(t) = 1 - \frac{t}{n} \tag{7}$$

First, the conditional probability of failure is evaluated at t^{th} year given that no failure occurs during years 1 through t-1. This probability can be calculated using Bayes' theorem (Ross 1997).

$$P\{\text{failure at year 1}\} = \frac{1}{n}$$

$$P\{\text{failure at year 2| no failure at year 1}\}$$

$$= \frac{P\{\text{failure at year 2, no failure at year 1}\}}{P\{\text{no failure at year 1}\}}$$

$$= \frac{P\{\text{no failure at year 1} | \text{failure at year 2}\}\, P\{\text{failure at year 2}\}}{P\{\text{no failure at year 1}\}}$$

$$= \frac{1 \times \dfrac{1}{n}}{1 - \dfrac{1}{n}} = \frac{1}{n-1}$$

$$P\{\text{failure at year 3 | no failure at year 2, no failure at year 1}\}$$

$$= \frac{P\{\text{failure at year 3, no failure at year 2, no failure at year 1}\}}{P\{\text{no failure at year 2, no failure at year 1}\}}$$

$$= \frac{P\{\text{no failure at year 2, no failure at year 1}|\text{failure at year 3}\}\, P\{\text{failure at year 3}\}}{P\{\text{no failure at year 2, no failure at year 1}\}}$$

$$= \frac{\dfrac{1}{n}}{\left(1-\dfrac{1}{n-1}\right)\left(1-\dfrac{1}{n}\right)} = \frac{1}{n-2}$$

By the same reasoning, it is concluded that

$$P\{\text{failure at year t} + 1 | \text{no failure from year 1 to year t}\} = \frac{1}{n-t} \tag{8}$$

It is interesting to point out that this probability is nothing but failure rate $\lambda(t-1)$ in a discrete case. Having realized this, the following relationship for reliability exists

$$R_c(t) = \exp\left(-\int_0^t \lambda(\tau)d\tau\right) = \exp\left(-\int_0^t \frac{1}{n-\tau}d\tau\right)$$

$$= \exp\left[\ln(n-\tau)\big|_0^t\right] = \frac{n-t}{n} = 1 - \frac{t}{n} \tag{9}$$

Thus, the conclusion is that the reliability of the navigation lock is $1 - t/n$, where n is the return period of the barge impact that has a load exceeding DMIL. Figure 15 shows the reliability as a function of time. One interesting thing to note is that if the return period is very long, namely if n is a very large number, then for those years satisfying $t \ll n$ we have $1 - t/n \approx e^{-t/n}$. This means that, for a fairly long period of time, the reliability function can be approximated by exponential function. This approximation is not just a mathematical convenience. It can provide added insight into the analysis, as will be shown below.

Likewise, if the probability that an earthquake whose magnitude in terms of ground motion exceeds the designed maximum ground motion (DMGM) strikes during a year is $1/m$, then the reliability of the lock is

$$R_q(t) = 1 - \frac{t}{m} \tag{10}$$

If both collision and earthquake are under consideration and independent, then the reliability of the lock structure due to these events is as follows:

$$R(t) = R_c(t)R_q(t) = \left(1 - \frac{t}{m}\right)\left(1 - \frac{t}{n}\right) \tag{11}$$
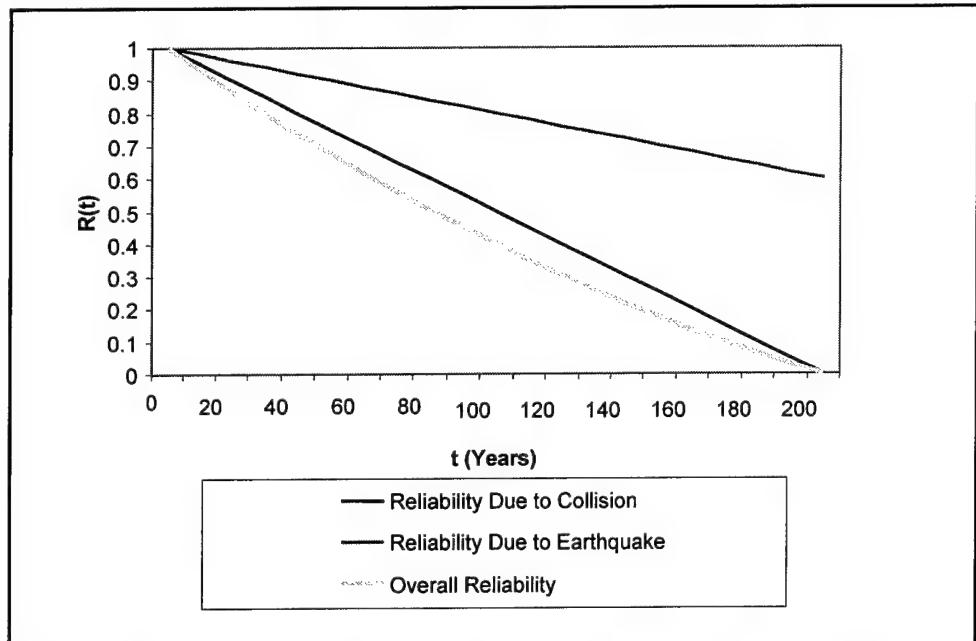
Figure 15. Reliability over time for individual and joint cases

Figure 15 shows the reliability as a function of time for individual and joint cases.

4.2 Mean Time to Failure Due to Single Failure Mode: A Probabilistic Approach

In Section 3.1 it was stated that the probability that a structure fails could be determined by the equation (Ellingwood 1995)

$$P(F) = \sum_i P(F|E_i) P(E_i) \qquad (3, \text{bis})$$

However, the contribution of loads below the DMIL to the failure of the structure was not explicitly addressed. From a strict probabilistic point of view, however, such loads could also contribute to failure. If this effect is taken into consideration, then

$$\overline{T} = \overline{\tau} \left[\frac{P(F|E_1)}{n_1} + \frac{P(F|E_2)}{n_2} + \ldots + \frac{P(F|E_k)}{n_k} \right]^{-1}$$

$$= \overline{\tau} \left[\sum_i \frac{P(F|E_i)}{n_i} \right]^{-1} = \overline{\tau} \left[\sum_i P(F|E_i) P(E_i) \right]^{-1} \qquad (12)$$

$$= \frac{\overline{\tau}}{P(F)}$$

where $\bar{\tau}$ is the mean arrival time of the events and $\bar{T}$ is the mean time to failure. The probabilities of load intervals would be defined as shown in Figure 16. In drawing the conclusion, it was assumed that event E_i ($i = 1, 2\ldots k$) constitutes a counting process with a mean arrival time n_i.
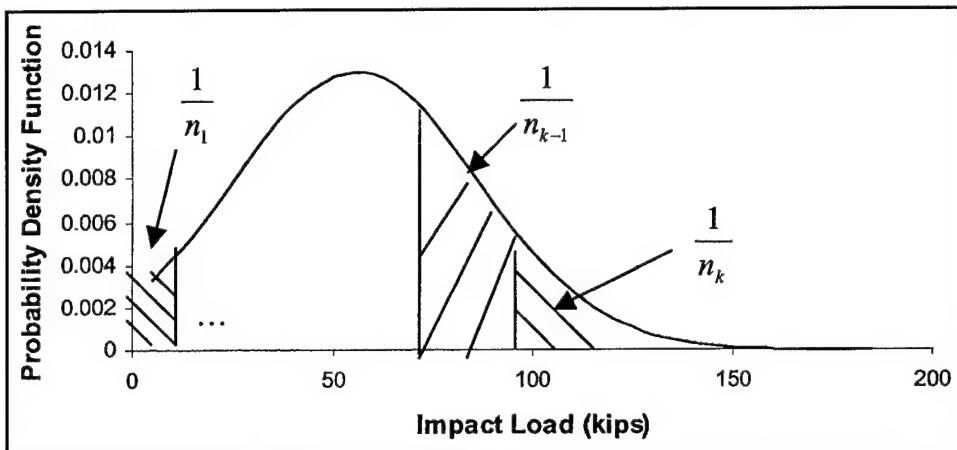
Figure 16. Probabilities of load intervals

4.3 Mean Time to Failure Due to Multiple Failure Modes

In this section, the joint effect of barge impact and earthquake loadings is investigated with regard to the MTTF of the lock structure. First, a few working assumptions are needed to understand the development of the joint MTTF for a lock.

4.3.1 Independence of attributes

Two decision variables have been used in this report: the designed maximum impact load and the designed maximum ground motion due to an earthquake. In physical reality, these two variables may have some kind of interdependence. For instance, an earthquake may cause a towboat to lose control and thereby hit a lock with enormous momentum. Nevertheless, it is an acceptable assumption in the conceptual design stage to assume that these two variables are totally independent. The engineering practice within USACE seems to be consistent with this assumption (EM 1110-2-6050, Patev 1999).

4.3.2 Independence of event series

Assume that different event series are independent and, more specifically, that as distinctive event series, collisions and earthquakes constitute independent stochastic processes. The compound effect of multiple failure modes can be described using a fault tree methodology (U.S. Nuclear Regulatory Commission 1981, Haimes 1998).

The joint effect of the multiple causes can be characterized by an "or" gate, as shown in Figure 17.
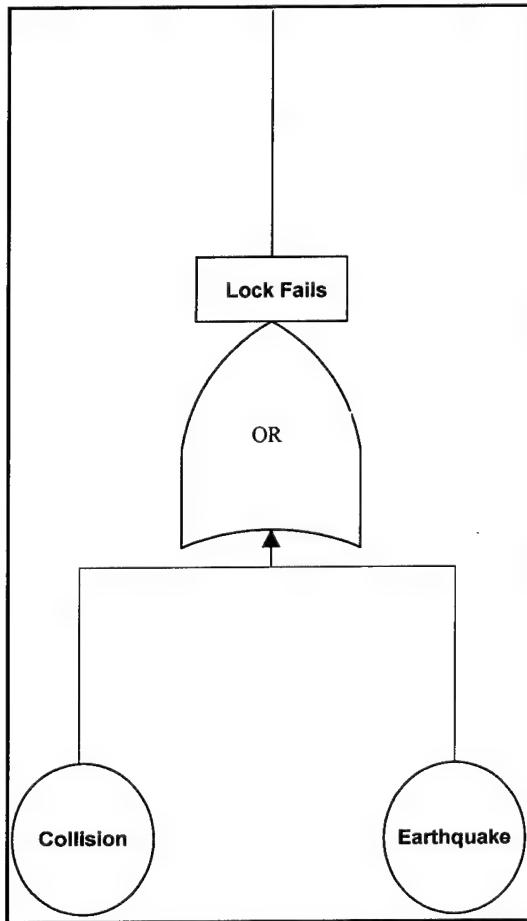
Figure 17.   Fault tree for compound failure

If $R_c(t)$ and $R_q(t)$ denote the reliability of the lock due to collision and earthquake, respectively, then the reliability of the lock due to both causes is

$$R(t) = R_c(t)R_q(t) \tag{13}$$

Likewise, if bombing by terrorists is another cause of failure, then correspondingly, the reliability of the lock can be written as

$$R(t) = R_c(t)R_q(t)R_b(t) \tag{14}$$

where $R_b(t)$ is the reliability of the lock due to bombing alone. Thus, the fault tree due to the three causes is as shown in Figure 18.

As pointed out previously, for a significant part of the life cycle, the reliabilities due to individual failure modes can be approximated as exponential distributions, that is, $R_c(t) = e^{-\lambda_c t}, R_q(t) = e^{-\lambda_q t}$, etc. If this is performed in this way, then the overall reliability of the lock is simply given as
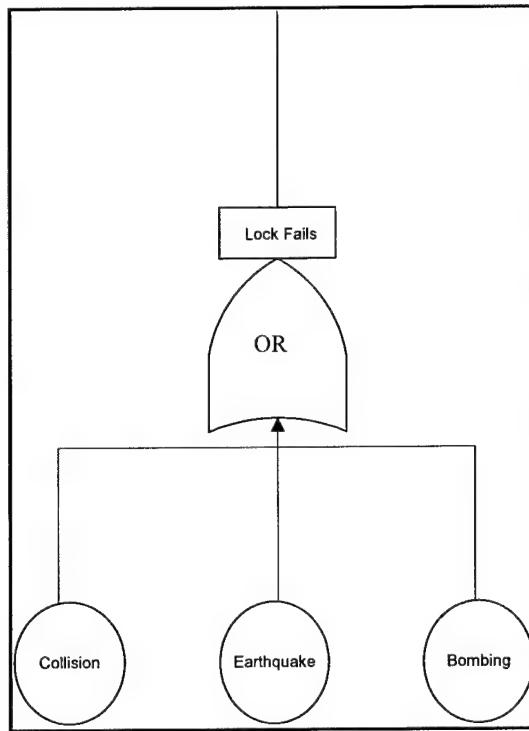
Figure 18.   Fault tree for compound failures

$$R(t) = R_c(t)R_q(t) = e^{-(\lambda_c + \lambda_q)t} \qquad (15)$$

which is an exponential distribution as well. It is easy to show mathematically that the mean time to failure, T, is given as

$$\overline{T} = \frac{1}{\lambda_c + \lambda_q} = \frac{1}{\frac{1}{T_c} + \frac{1}{T_q}} = \frac{T_c T_q}{T_c + T_q} \qquad (16)$$

Exponential reliability implies that the failure or hazard rate does not vary with time, which is not strictly true, even though the failure of the system considered here is not a result of an internal flaw but a consequence of single or multiple external impacts. As a matter of fact, since the lock is a structure that undergoes degradation (aging or time dependence) over time, it is expected that the failure rate should increase over time as well (see Equation 7). A nonvarying failure rate can be used as an approximation only when the time under consideration is significantly shorter than the planned life cycle.

4.3.3 Failure modes as Poisson arrivals

By assuming that the reliability due to each individual failure mode observes an exponential distribution, another assumption is implied: that each of the failure modes constitutes a Poisson process on its own. A number of authors (Larrabee and Cornell 1981, Pearce and Wen 1984, Ellingwood 1995) have

modeled the occurrence of potentially hazardous events giving rise to time-dependent structural loads as a Poisson process. Mathematically, one can show that if there are two series of discrete events, E_1 and E_2, each of them constituting a Poisson process (Ross 1997) on its own, then the compound process, or the combination of these two processes, also constitutes a Poisson process. The arrival rate of this compound process is the summation of the arrival rates of the two individual processes. In our discussion, instead of modeling all incoming hazardous events, the assumption is to model the incoming events that lead to failure of the structure as a Poisson's process as well. As an example, assume that barge impact events exceed the DMIL. Those earthquakes that generate ground acceleration exceeding the DMGM also follow a Poisson process.

Observation 1. If a system fails due to any event in any one of the following N distinct series of events, $E_1, E_2 \ldots E_i \ldots E_N$, and if

(1) Event in series E_i ($i = 1,2 \ldots N$) has a mean return period T_i

(2) Series E_i ($i = 1,2 \ldots N$) constitutes a Poisson process

Then, the mean time for the system to fail is

$$T = \frac{1}{\frac{1}{T_1} + \frac{1}{T_2} + \cdots + \frac{1}{T_N}} \tag{17}$$

(***Proof***: See Appendix A.)

Remark: Since $\dfrac{1}{T_i} < \dfrac{1}{T_1} + \dfrac{1}{T_2} + \ldots \dfrac{1}{T_N} = \dfrac{1}{T}$, we know that $T < T_i$, $i = 1,2 \ldots N$.

This means that the MTTF of the system due to the multiple causes is less than the MTTF due to any single cause. Observation 1 makes it possible to evaluate the new MTTF given that the individual times are known.

Applying this result to our problem, the MTTF of a navigation lock is shortened by a multiplicity of causes. In other words, the MTTF of the system due to both collision and earthquake is shorter than it would be if there were one cause only (either collision or earthquake). Mathematically, if the MTTF allowing for collision only is T_1, and that allowing for earthquake only is T_2, then the MTTF due to both causes is $\dfrac{T_1 T_2}{T_1 + T_2}$. Furthermore, if the system is also subject to failure due to terrorist bombing for example, and the return period for the bombing is T_3, then the actual MTTF is

$$T = \frac{T_1 T_2 T_3}{T_1 T_2 + T_2 T_3 + T_3 T_1} \tag{18}$$

4.3.4 Failure modes as general stochastic arrivals

Now consider the failure modes in a more general setting. Consider a counting process $N(t)$ with rate λ. Suppose $f(\lambda, k)$ denotes the point probability distribution that $N(t+1) - N(t) = k, k = 0,1,2\ldots$, for a given t. Then $f(\lambda, k)$ must satisfy the following relationships:

(1) $\quad f(\lambda, k) \geq 0$

(2) $\quad \displaystyle\sum_{k=0}^{\infty} f(\lambda, k) = 1$ $\hspace{4cm}$ (19)

(3) $\quad \displaystyle\sum_{k=0}^{\infty} kf(\lambda, k) = \lambda$

Conversely, any $f(\lambda, k)$ that satisfies relationship (1) – (3) in Lemma 2 defines a counting process with rate λ.

Now note the following important observations:

Observation 2. Let $N_1(t)$ and $N_2(t)$ denote two counting processes with rates λ and μ, respectively. Let $f(\lambda, k)$ denote the point probability distribution that $N_1(t+1) - N_1(t) = k, k = 0,1,2\ldots$, for a given t, and $g(\mu, k)$ denote the point probability distribution that $N_2(t+1) - N_2(t) = k, k = 0,1,2\ldots$, for a given t. The compound process of $N_1(t)$ and $N_2(t)$ is also a counting process with rate $\lambda + \mu$.

(Proof: See Appendix A.)

Observation 3. If a system fails due to an event in any one of the following N distinct series of events, $E_1, E_2 \ldots E_i \ldots E_N$, and if

(1) Event in series E_i $(i = 1,2\ldots N)$ has a mean return period T_i

(2) Series $E_i (i = 1,2\ldots N)$ constitutes a counting process

Then, the mean time for the system to fail is

$$T = \frac{1}{\frac{1}{T_1} + \frac{1}{T_2} + \ldots + \frac{1}{T_N}}$$

This observation is a generalization of Observation 1. Again, since

$$\frac{1}{T_i} < \frac{1}{T_1} + \frac{1}{T_2} + \cdots \frac{1}{T_N} = \frac{1}{T}$$

it is known that $T < T_i$, $i = 1, 2 \ldots N$. This means that the mean time to failure of a system due to the multiple causes is less than the MTTF due to any single cause. Using this result, the evaluation of the MTTF of a navigation lock due to multiple causes is based on the knowledge of times of occurrence for each individual cause. Owing to this observation, there is no longer a need to rely on the failure modes being Poisson processes. From a reliability standpoint, often the reliability function $R(t)$ is not known exactly due to scarcity of data. Typically, what is known with a certain degree of confidence is the MTTF. Observation 3 simply states that if the mean times to failure due to the individual causes are known, then one can evaluate the MTTF due to multiple causes without knowledge of the reliability function.

Table 4 shows the mean times to failure due to collision and earthquake for different DMIL and DMGM.

Table 4
Mean Time to Failure Due to Collision and Earthquake

DMIL, kips	DMGM, g	Mean Time to Failure, years	T_1, years[1]	T_2, years[1]
610	0.2	1.952	2	81.473
680	0.2	4.710	5	81.473
810	0.2	30.984	50	81.473
840	0.2	44.895	100	81.473
920	0.2	70.057	500	81.473
950	0.2	75.335	1,000	81.473
610	0.25	1.959	2	96.576
680	0.25	4.753	5	96.576
810	0.25	32.944	50	96.576
840	0.25	49.129	100	96.576
920	0.25	80.942	500	96.576
950	0.25	88.071	1,000	96.576
610	0.3	1.968	2	126.494
680	0.3	4.809	5	126.494
810	0.3	35.835	50	126.494
840	0.3	55.848	100	126.494
920	0.3	100.954	500	126.494
950	0.3	112.290	1,000	126.494
610	0.35	1.978	2	185.759
680	0.35	4.868	5	185.759
810	0.35	39.395	50	185.759
840	0.35	65.005	100	185.759
920	0.35	135.440	500	185.759
950	0.35	156.658	1,000	185.759
610	0.4	1.986	2	303.156
680	0.4	4.918	5	303.156
810	0.4	42.920	50	303.156
840	0.4	75.195	100	303.156
920	0.4	188.728	500	303.156
950	0.4	232.632	1,000	303.156
610	0.45	1.992	2	535.708
680	0.45	4.953	5	535.708
810	0.45	45.731	50	535.708
840	0.45	84.269	100	535.708
920	0.45	258.619	500	535.708
950	0.45	348.834	1,000	535.708
610	0.5	1.995	2	996.369
680	0.5	4.975	5	996.369
810	0.5	47.610	50	996.369
840	0.5	90.878	100	996.369
920	0.5	332.928	500	996.369

[1] T_1 is the mean time to failure due to collisions only. T_2 is the mean time to failure due to earthquakes only.

5 Risk Management of Compound Failure Modes

Johnson-Payton (1997) described a methodology for risk management of compound failure modes. The methodology can be outlined as follows:

First, consider a system that can fail in n different ways (failure modes). Failure mode i is described by the binary random variable, x_i, which equals 1 if failure mode i occurs and 0 otherwise. Suppose there are only two failure modes. Let p_{kl} denote the probability of $x_1 = k$ and $x_2 = l$. Let c_{kl} represent the consequence of $x_1 = k$ and $x_2 = l$, which can be monetary loss, lives lost, property destruction, or any combination of these. In general c_{kl} is a random variable with probability density function $f(c_{kl})$.

Given the above information, one can calculate the expected cost { $E[c(\mathrm{x})]$ } and the partitioned conditional expected cost corresponding to extreme risk for each individual failure mode as well as for the compound failure modes. In general, different policy options correspond to different cost-risk relations. Thus, a multi-objective tradeoff analysis provides a conceptual framework for addressing cost-risk tradeoffs due to compound failure modes. However, Johnson-Payton (1997) does not consider the continuous aspect of many real problems. In fact, between perfection and complete failure there is normally a spectrum of "partial" failures, which correspond to varying levels of risks. Mathematically, this means x can be a continuous random variable, taking on real values between 0 and 1, with 0 corresponding to perfection and 1 corresponding to complete failure. In this section, we will extend this idea to compound failure modes analysis and apply the methodology to perform a cost-risk analysis for the lock and dam problem.

5.1 Conceptual Framework of Partial Failure Analysis

A barge impact on a navigation structure may cause the system to function partially while repair work is under way. This illustrates the need to address the partial nature of failure.

Let $x = (x_1, x_2 \ldots x_n)$ denote a vector of failure mode, termed a *failure vector*, where $x_i \in [0,1]$, $i = 1, 2 \ldots n$. Let $g(x) \equiv g(x_1, x_2 \ldots x_n)$ be the probability density function of x. Let $c(x)$ be the consequence (e.g. lives lost or monetary damage) of failure x. Let $f[c(x)]$ denote the probability density function of $c(x)$. Then, the expected damage f_5 can be calculated as

$$E[c(x)]
= \iint \cdots \int c(x_1, x_2 \ldots x_n) f[c(x_1, x_2 \ldots x_n)] g(x_1, x_2 \ldots x_n) \delta c dx_1 dx_2 \ldots dx_n \tag{20}$$

and the extreme risk function is

$$E[c(\mathrm{x}) \mid c(\mathrm{x}) > r]
= \frac{\displaystyle\iint_{c>r} c(x_1, x_2 \ldots x_n) f[c(x_1, x_2 \ldots x_n)] g(x_1, x_2 \ldots x_n) \delta c dx_1 dx_2 \ldots dx_n}{\displaystyle\int_{c>r} f[c(x_1, x_2 \ldots x_n)] g(x_1, x_2 \ldots x_n) \delta c dx_1 dx_2 \ldots dx_n} \tag{21}$$

where r is the partitioning point in the region of extreme risk.

Different failure modes can be interdependent. For example, an earthquake may also cause collisions and, eventually, the concurrent action of these two failure modes can result in the failure of a navigation lock. Nevertheless, in many cases it is a reasonable approximation to assume the independence of different failure modes. For example, using the probabilistic event combination techniques, Ellingwood (1995) has shown that the probability of a simultaneous earthquake and barge impact is on the order of 10^{-15}. Thus, from any practical standpoint, these two types of events can be considered as independent. Needless to say, the independence assumption can bring about significantly simpler mathematical treatment. One direct consequence of the independence assumption is that, if the independence assumption holds, then $x_1, x_2 \ldots x_n$ are independent random variables. Thus, Equations 20 and 21 lead to Equations 22 and 23.

$$E[c(\mathrm{x})] = \iint \cdots \int (c_1(x_1) + \ldots + c_n(x_n)) f_1[c_1(x_1)] \ldots f_n[c_n(x_n)] g_1(x_1) \ldots g_n(x_n) \delta c_1 \ldots \delta c_n dx_1 \ldots dx_n$$

$$= \sum_{i=1}^{n} \iint c_i(x_i) f_i[c_i(x_i)] g_i(x_i) \delta c_i dx_i \tag{22}$$

and

$E[c(\mathbf{x}) \mid c(\mathbf{x}) > r]$

$$= \frac{\iint \cdots \int\limits_{c_1+c_2+\ldots+c_n>r} [c_1(x_1)+\ldots+c_n(x_n)] f_1[c_1(x_1)]\ldots f_n[c_n(x_n)]g_1(x_1)\ldots g_n(x_n)\delta c_1\ldots\delta c_n dx_1\ldots dx_n}{\iint \cdots \int\limits_{c_1+c_2+\ldots+c_n>r} f_1[c_1(x_1)]\ldots f_n[c_n(x_n)]g_1(x_1)\ldots g_n(x_n)\delta c_1\ldots\delta c_n dx_1\ldots dx_n} \tag{23}$$

$$= \frac{1-\iint \cdots \int\limits_{c_1+c_2+\ldots+c_n<r} [c_1(x_1)+\ldots+c_n(x_n)] f_1[c_1(x_1)]\ldots f_n[c_n(x_n)]g_1(x_1)\ldots g_n(x_n)\delta c_1\ldots\delta c_n dx_1\ldots dx_n}{1-\iint \cdots \int\limits_{c_1+c_2+\ldots+c_n<r} f_1[c_1(x_1)]\ldots f_n[c_n(x_n)]g_1(x_1)\ldots g_n(x_n)\delta c_1\ldots\delta c_n dx_1\ldots dx_n}$$

The mathematical details of the derivation are shown in Appendix B. The following section outlines an application of these ideas to analyze the hazards of a navigation lock subject to barge impact and earthquake loads.

5.2 Application to Risk Assessment for Navigation Locks

Consider a river navigation lock that could be subject to impacts of both collisions and earthquakes. Let x_1 denote the failure mode due to collision and x_2 denote the failure mode due to earthquake. As noted above, x_1 and x_2 are continuous random variables and can take on any value between 0 and 1, with 0 representing no failure (meaning that no collision or earthquake occurs) and 1 representing a complete failure that leads to a complete dysfunctional system. This could lead to the potential destruction and collapse of the system. Assume that these two failure modes are independent and therefore their consequences are additive. Let $c_1(x_1)$ and $c_2(x_2)$ represent the consequences (damages, converted to monetary value in millions of dollars) caused by x_1 and x_2, respectively, which are normally distributed with mean and variance $(0.5x_1, 0.1x_1)$ [1] and $(2x_2, 0.4x_2)$, respectively. Hence, using the technique developed earlier in this report, the calculation of the unconditional expected damage and conditional expected damage in the region of extreme risk can be performed.

Suppose the following five policy options are considered, and each one is more sturdy than the last.

Policy 1: If the Corps spends $1.2 million to build the lock, then it is expected that x_1 is an $N(0.50, 0.20)$ variable and x_2 is an $N(0.30, 0.10)$ variable.

Policy 2: If the Corps spends $1.4 million, then it is expected that x_1 is an $N(0.40, 0.1)$ variable and x_2 is an $N(0.25, 0.09)$ variable.

---

[1] All normal distributions in this chapter are truncated and accordingly normalized to ensure nonnegativity.

Policy 3: If the Corps spends $1.6 million, then it is expected that x_1 is an $N(0.30, 0.1)$ variable and x_2 is an $N(0.20, 0.08)$ variable.

Policy 4: If the Corps spends $1.8 million, then it is expected that x_1 is an $N(0.25, 0.08)$ variable and x_2 is an $N(0.18, 0.05)$ variable.

Policy 5: If the Corps is willing to spend $2 million, then one can further decrease the hazard due to both collisions and earthquakes so that x_1 is an $N(0.20, 0.05)$ variable and x_2 is an $N(0.15, 0.04)$ variable.

Thus, by using Equations 22 and 23, one can calculate the unconditional expected damage and conditional expected damage in the extreme region (partitioned at 2σ, where σ is the standard deviation). The results from each policy decision are shown in Table 5 (with costs and the damages in millions of dollars).

Table 5
Example Policies and Associated Costs and Risks

Policy	Cost, M$	x1, M$	x2, M$	f5(1) , M$	f5(2) , M$	f5, M$	f4(1) , M$	f4(2) , M$	f4, M$
1	1.20	$N(0.50, 0.20)$	$N(0.30, 0.10)$	0.03110	0.1508	0.18190	0.3683	0.8861	1.2544
2	1.40	$N(0.40, 0.10)$	$N(0.25, 0.09)$	0.01260	0.1131	0.12570	0.2947	0.7395	1.0342
3	1.60	$N(0.30, 0.10)$	$N(0.20, 0.08)$	0.00940	0.0805	0.08990	0.2213	0.5939	0.8152
4	1.80	$N(0.25, 0.08)$	$N(0.18, 0.05)$	0.00630	0.0452	0.05150	0.1844	0.5309	0.7153
5	2.00	$N(0.20, 0.05)$	$N(0.15, 0.04)$	0.00314	0.0301	0.03324	0.1473	0.4423	0.5896

where

    x1   = amount of damage from collision

    x2   = amount of damage from earthquake

    f5(1) = expected value of damage from collision

    f5(2) = expected value of damage from earthquake

    f5   = expected value of damage from both collision and earthquake

    f4(1) = conditional expected value of damage in the extreme region from collision

    f4(2) = conditional expected value of damage in the extreme region from earthquake

    f4   = conditional expected value of damage in the extreme region from both collision and earthquake

The cost-risk relationships for the five policies are shown in Figures 19-22. It is evident that, although the expected damages are not high, the conditional expected damages could be extraordinarily high. It is also clear that the decision-maker must make a tradeoff in order to strike a balance between construction costs and the robustness of the lock. Although the five policies all appear to be Pareto solutions, there may be a specific utility function that renders one policy particularly favorable.
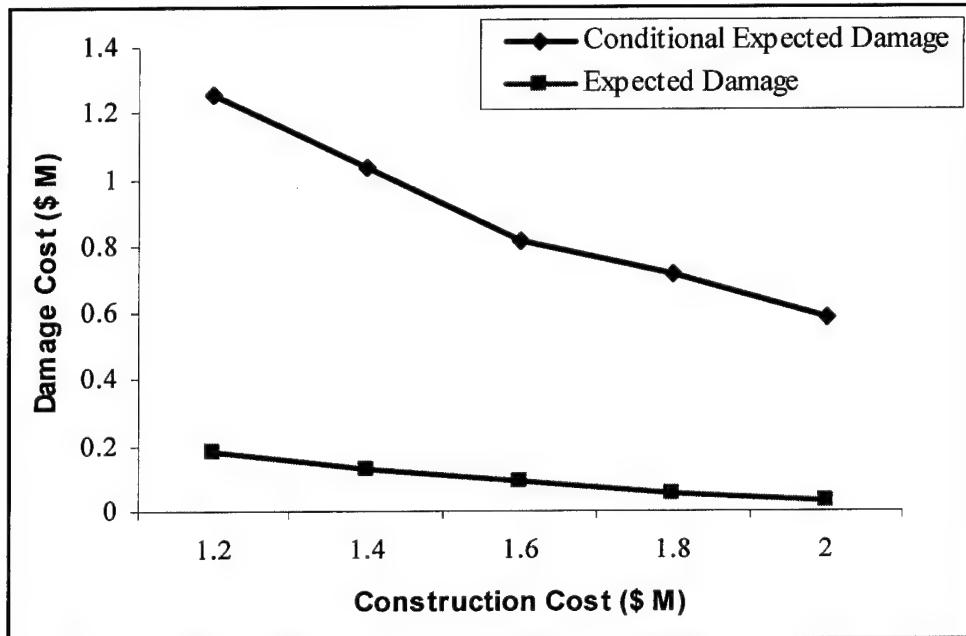

Figure 19.   Risk due to multiple failures versus construction cost
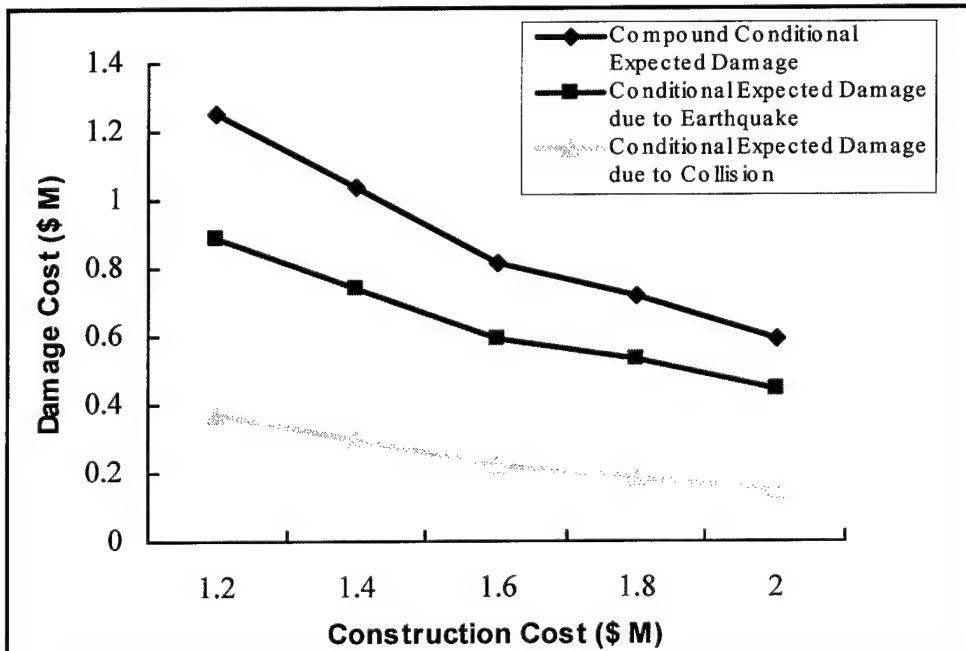
Figure 20.   Risk due to extreme events versus construction cost
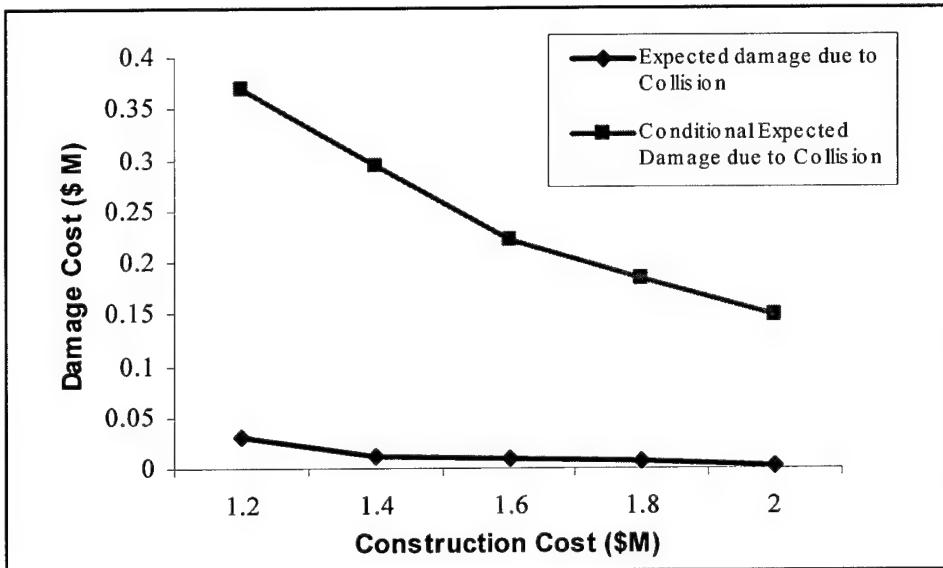
Figure 21. Risk due to collision versus construction cost
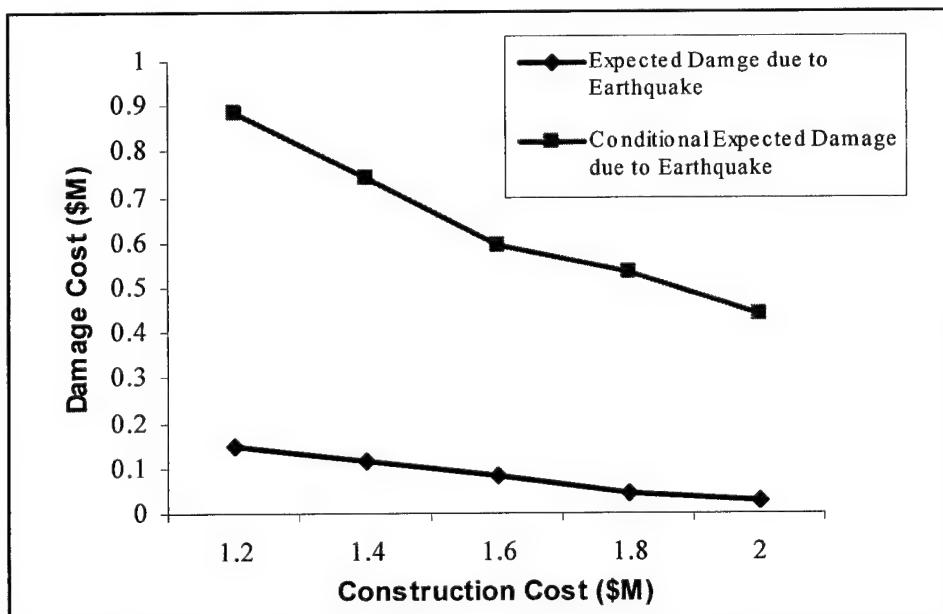
Figure 22. Risk due to earthquake versus construction cost

6 Recommendations

The following are the recommendations required for Phase 2 of the research and are based on the results and conclusions of Phase 1. A recommendation to adopt the developed methods of modeling the occurrences of compound failure modes as a Poisson and a general counting process is made. Furthermore, because many accidents are caused by rapidly rising water levels common in floods (ASCE 1998 and other sources[1]), the model may advance along the following lines: find the probability density function (pdf) of floods in terms of water levels at the site in question; then, find the pdf of collisions in terms of impact force conditioned on given water levels by noting the collisions that have occurred at locks in a geographical region. Look at regional data if data on specific site collisions are scarce; find the pdf of direct damage due to a given impact, in terms of dollars.

Another way to model extreme events such as barge impacts is scenario analysis (Kaplan 1996). This method is especially useful when data are scarce, which is the case with lock failures. Since the amount of barge traffic and the barge sizes in the future are uncertain, forecasting models using regression and time series can be developed.

Another factor that warrants a closer look is the indirect damage, or cost due to shutting down the facility and using alternate ways to transport goods. This may affect the final tradeoff analysis, as an even more conservative design may be warranted if the indirect cost turns out to be the overriding one. Once the damages due to different failure modes can be reliably estimated (assisted by the methodology developed in Phase 1 and the model advancement mentioned previously), it is recommended that the USACE

- Consider complete failures by trading off construction cost for life expectancy of lock.

- Consider partial failures by looking at tradeoffs between

  1) Cost incurred by failure and cost of building the structure initially.

  2) Ratio of repair cost over reconstruction cost.

  3) Ratio of impact load over the maximum impact the structure could withstand.

---

[1] Personal Communication, 15 Dec 1999, Professor Roman Krzysztofowicz, Statistician, University of Virginia, Charlottesville.

In addition, the following data are needed to perform the recommended tasks in Phase 2:

- Detailed information about specific locks, including diagram of structure, materials used, maximum allowable stress, etc.

- Loss to businesses due to shutdown of a lock.

- Planning and construction costs of new locks. (Useful source: *Design Memorandums* for Corps lock facilities.)

- Repair and reconstruction costs due to partial or complete failure.

- Corps' method for assessing reliability of navigation.

- Historical frequencies of earthquakes of different magnitudes in the vicinity of the locks.

- Historical data on barge impacts: mass and sizes of barges, damages incurred, and dates of impacts. (Possible source: accident database maintained by the U.S. Coast Guard.)

- Experimental/field results on angles and velocities of barge impacts to locks with new designs.

- Most current data on the mass and sizes of barge tows and their per-event probabilities.

- Water levels at specific sites at the times of collisions.

Once the above data are obtained, the actual probability distributions of barge impacts and earthquakes can be incorporated into the study so that a more solid understanding of reliability and mean time to failure can be obtained. Then, the methodology developed in Phase 1 can be implemented as a computer program to aid decision-making.

To ensure the accuracy and robustness of the model's output, one must account for the scarcity or lack of data, as this may lead to parameter uncertainty in the model. To assess the robustness of the model, one must conduct a sensitivity analysis in Phase 2. In this, the goals are to

- Evaluate the dominant parameters that will have major impacts on the expected direct and indirect costs.

- Evaluate the conditional expected costs in the region of extreme risk.

- Identify parameters to which the cost is insensitive.

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Appendix A
Example Problem

Proof of Observation 1:

First, the expected interarrival time for the compound Poisson process is $\frac{1}{T_1} + \frac{1}{T_2} + \ldots \frac{1}{T_N}$. The method of mathematical induction is used to prove this.

The arrival rate of process E_i is, obviously, $\frac{1}{T_i}$. First, consider two processes, E_1 and E_2. From the preceding lemma, it is known that the compound process of these two is a Poisson process with arrival rate $\frac{1}{T_1} + \frac{1}{T_2}$. Second, suppose the arrival rate of the compound process of $E_1, E_2 \ldots E_i$ is $\frac{1}{T_1} + \frac{1}{T_2} + \ldots \frac{1}{T_i}$. Then, from the preceding lemma, the arrival rates of the compound process of $E_1, E_2 \ldots E_i$ and E_{i+1} is $\left(\frac{1}{T_1} + \frac{1}{T_2} + \ldots \frac{1}{T_i} \right) + \frac{1}{T_{i+1}}$. This proves that the expected interarrival time for the compound Poisson process is

$$T = \frac{1}{\frac{1}{T_1} + \frac{1}{T_2} + \ldots + \frac{1}{T_N}}.$$

Now that any event in this compound process can cause the system to fail, the mean time for the system to fail is $T = \dfrac{1}{\frac{1}{T_1} + \frac{1}{T_2} + \ldots + \frac{1}{T_N}}.$

Proof of Observation 2:

Let $N(t)$ denote the compound process. Let $h(\gamma, k)$ denote the point probability distribution that $N(t+1) - N(t) = k, k = 0, 1, 2 \ldots$. Obviously,

$$h(\gamma, k) = \sum_{k'=0}^{k} f(\lambda, k - k') g(\mu, k')$$

Note that

$$\sum_{k=0}^{\infty} h(\gamma, k) = \sum_{k=0}^{\infty} \sum_{k'=0}^{k} f(\lambda, k - k') g(\mu, k')$$

$$= \sum_{k'=0}^{\infty} g(\mu, k') \sum_{k-k'=0}^{\infty} f(\lambda, k - k') = 1$$

Furthermore,

$$\sum_{k=0}^{\infty} k h(\gamma, k) = \sum_{k=0}^{\infty} \sum_{k'=0}^{k} k f(\lambda, k - k') g(\mu, k')$$

$$= \sum_{k=0}^{\infty} \sum_{k'=0}^{k} (k' + k - k') f(\lambda, k - k') g(\mu, k')$$

$$= \sum_{k=0}^{\infty} \sum_{k'=0}^{k} k' f(\lambda, k - k') g(\mu, k') + \sum_{k=0}^{\infty} \sum_{k'=0}^{k} (k - k') f(\lambda, k - k') g(\mu, k')$$

$$= \sum_{k'=0}^{\infty} k' g(\mu, k') \sum_{k-k'=0}^{\infty} f(\lambda, k - k') + \sum_{k'=0}^{\infty} g(\mu, k') \sum_{k-k'=0}^{\infty} (k - k') f(\lambda, k - k')$$

$$= \mu + \lambda$$

Thus, it is clear that $N(t)$ is a counting process with rate $\lambda + \mu$.

Appendix B
Mathematical Details for Partial Failure Modes

Calculations. Let $x = (x_1, x_2 \ldots x_n)$ denote a vector of a failure mode, termed a *failure vector*, where $x_i \in [0,1]$, $i = 1, 2 \ldots n$. Let $g(x) \equiv g(x_1, x_2 \ldots x_n)$ be the probability density function of x. Let $c(x)$ be the consequence (e.g., lives lost or monetary damage) of failure x. Let $f[c(x)]$ denote the probability density function of $c(x)$. Then, the expected damage f_s can be calculated as

$$E[c(x)] = \iint \cdots \int c(x_1, x_2 \ldots x_n) f[c(x_1, x_2 \ldots x_n)] g(x_1, x_2 \ldots x_n) \delta c dx_1 dx_2 \ldots dx_n \tag{B1}$$

and the extreme-risk function as

$$E[c(x) | c(x) > r] = \frac{\displaystyle\iint_{c>r} c(x_1, x_2 \ldots x_n) f[c(x_1, x_2 \ldots x_n)] g(x_1, x_2 \ldots x_n) \delta c dx_1 dx_2 \ldots dx_n}{\displaystyle\int_{c>r} f[c(x_1, x_2 \ldots x_n)] g(x_1, x_2 \ldots x_n) \delta c dx_1 dx_2 \ldots dx_n} \tag{B2}$$

where r is the partitioning point in the region of extreme risk.

Likewise, the unconditional and conditional risk function can be calculated for any individual failure mode, or any combination of individual failure modes. For instance, if one wants to calculate $E[c(\mathbf{x})]$ and $E[c(x) | c(x) > r]$ for failure mode 1, then

$$E[c(x)] = \frac{\displaystyle\iint c(x_1, 0 \ldots 0) f[c(x_1, 0 \ldots 0)] g(x_1, 0 \ldots 0) \delta c dx_1}{\displaystyle\int f[c(x_1, 0 \ldots 0)] g(x_1, 0 \ldots 0) \delta c dx_1} \tag{B3}$$

and

$$E[c(\mathbf{x}) | c(x) > r] = \frac{\displaystyle\iint_{c>r} c(x_1, 0 \ldots 0) f[c(x_1, 0 \ldots 0)] g(x_1, 0 \ldots 0) \delta c dx_1}{\displaystyle\int_{c>r} \int f[c(x_1, 0 \ldots 0)] g(x_1, 0 \ldots 0) \delta c dx_1} \tag{B4}$$

If one is interested in obtaining $E[c(x)$ and $E[c(x)|c(x)>r]$ for compound failure modes x_i and x_j, then

$$E[c(\mathbf{x})] = \frac{\iiint c(0,...,x_i,...x_j,...,0)f[c(0,...,x_i,...x_j,...,0)]g(0,...,x_i,...,x_j,...,0)\delta c dx_i dx_j}{\iiint f[c(0,...,x_i,...,x_j,...,0)]g(0,...x_i,...,x_j,...,0)\delta c dx_i dx_j} \qquad (B5)$$

and

$$E[c(\mathbf{x})|c(\mathbf{x})>r] = \frac{\iint\limits_{c>r}\int c(0,...,x_i,...x_j,...,0)f[c(0,...,x_i,...x_j,...,0)]g(0,...,x_i,...,x_j,...,0)\delta c dx_i dx_j}{\int\limits_{c>r}\iint f[c(0,...,x_i,...,x_j,...,0)]g(0,...x_i,...,x_j,...,0)\delta c dx_i dx_j} \qquad (B6)$$

Proposition 1: If $x_i^{(1)} \le x_i^{(2)}$, and $x_j^{(1)} = x_j^{(2)}$ for all $j \ne i$, then

$$\int f[c(x_1^{(1)},...,x_i^{(1)},...x_n^{(1)})]c(x_1^{(1)},...,x_i^{(1)},...,x_n^{(1)})\delta c$$

$$\qquad (B7)$$

$$\le \int f[c(x_1^{(2)},...,x_i^{(2)},...x_n^{(2)})]c(x_1^{(2)},...,x_i^{(2)},...,x_n^{(2)})\delta c$$

This inequality simply says that the expected value of the damage is a nondecreasing function of any x. In other words, if the failure increases, then the expected damage will not decrease, and in reality, the expected damage will most likely increase.

Independence of failure modes. Failure modes can be independent and interdependent. For instance, earthquakes and collisions can each result in failure of a navigation lock. However, an earthquake may also cause collisions to occur, and eventually more damage will be caused by the concurrent action of these two failure modes. This is an example of the interdependence of different failure modes. Nevertheless, in many cases it is reasonable to assume the independence of different failure modes. Needless to say, the independence assumption can significantly simplify mathematical calculations. One direct consequence is that, if the independence assumption holds, then $x_1, x_2 ... x_n$ are independent random variables. Thus the joint distribution of $x_1, x_2 ... x_n$ can be written

$$g(x_1, x_2 ... x_n) = \prod_{i=1}^{n} g_i(x_i) \qquad (B8)$$

where $g_i(x_i)$ is the marginal distribution of x_i, where $i = 1, 2 ... n$, and the symbol $\prod$ denotes the product.

If the damage caused by independent failure modes is additive, then the damage function can be written as

$$c(x_1, x_2 \ldots x_n) = \sum_{i=1}^{n} c_i(x_i) \qquad \text{(B9)}$$

where $c_i(x_i)$ is the damage caused by failure mode x_i only, namely,

$$c_i(x_i) = c(0 \ldots, x_i \ldots, 0) \qquad \text{(B10)}$$

Obviously, $c_i(0) = 0$, $i = 1, 2 \ldots n$. It should be noted that, in reality, the compound damage of multiple failure modes may not be additive.

If the independence of failure modes holds and the damage is indeed additive, then

$$f[c(x_1, x_2 \ldots x_3)] = \prod_{i=1}^{n} f_i[c_i(x_i)] \qquad \text{(B11)}$$

$$\delta c = \prod_{i=1}^{n} \delta c_i \qquad \text{(B12)}$$

Therefore, one has the following important results:

$$E[c(\mathrm{x})] = \iint \cdots \int [c_1(x_1) + \ldots + c_n(x_n)] f_1[c_1(x_1)] \ldots f_n[c_n(x_n)] g_1(x_1) \ldots g_n(x_n) \delta c_1 \ldots \delta c_n dx_1 \ldots dx_n$$

$$= \sum_{i=1}^{n} \iint c_i(x_i) f_i[c_i(x_i)] g_i(x_i) \delta c_i dx_i \qquad \text{(B13)}$$

and

$$E[c(\mathrm{x}) \mid c(\mathrm{x}) > r]$$

$$= \frac{\displaystyle\iint \cdots \int_{c_1+c_2+\ldots+c_n > r} [c_1(x_1) + \ldots + c_n(x_n)] f_1[c_1(x_1)] \ldots f_n[c_n(x_n)] g_1(x_1) \ldots g_n(x_n) \delta c_1 \ldots \delta c_n dx_1 \ldots dx_n}{\displaystyle\iint \cdots \int_{c_1+c_2+\ldots+c_n > r} f_1[c_1(x_1)] \ldots f_n[c_n(x_n)] g_1(x_1) \ldots g_n(x_n) \delta c_1 \ldots \delta c_n dx_1 \ldots dx_n}$$

$$= \frac{1 - \displaystyle\iint \cdots \int_{c_1+c_2+\ldots+c_n < r} [c_1(x_1) + \ldots + c_n(x_n)] f_1[c_1(x_1)] \ldots f_n[c_n(x_n)] g_1(x_1) \ldots g_n(x_n) \delta c_1 \ldots \delta c_n dx_1 \ldots dx_n}{1 - \displaystyle\iint \cdots \int_{c_1+c_2+\ldots+c_n < r} f_1[c_1(x_1)] \ldots f_n[c_n(x_n)] g_1(x_1) \ldots g_n(x_n) \delta c_1 \ldots \delta c_n dx_1 \ldots dx_n}$$

$$\text{(B14)}$$

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14. ABSTRACT

This report summarizes the research efforts performed to date in support of the U.S. Army Corps of Engineers (USACE) to make design decisions pertaining to the innovative construction of navigation locks to minimize construction costs. This research project consists of two phases: Phase 1, which culminates with this report, investigated the use of multiple-criteria decision-making in the design process of lock approach walls to consider barge impact and earthquake loads. Phase 2 involves the development a computer programming tool that uses the previously developed methodology and its application to case studies for innovative lock approach walls.

After reviewing the available literature, featuring various USACE engineering manuals and papers on the methodology of multiple-criteria decision-making, the research efforts were focused on hazard and reliability analysis due to multiple failure modes. Realizing that navigation structures are vulnerable to barge impacts, earthquakes, operational errors, and extreme events such as bombings, a conceptual framework was initially developed for analyzing the consequences of barge impacts and earthquakes. The reliability was also evaluated as a function of time for a "generic" navigation lock due to the joint potential for both collision and earthquake. A mathematical scheme was developed to evaluate the mean time to failure of a lock structure due to multiple causes.

(Continued)

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Barge	Hazard	Multiple-criteria	System reliability
Decision-making	Innovative	Reliability	Tradeoff analysis

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Another primary thrust of this research project focused on tradeoff analysis. The objectives of multiple-criteria decision-making are to minimize both construction cost and repair damage caused by incipient failures. This report did not directly consider design and construction costs. Rather, the focus was on the robustness of a navigation structure as measured by the designed maximum impact force and the designed maximum ground motion that the structure could experience. The impacts of partial or complete failures on different designs were evaluated. The results show that a direct tradeoff has to be made in order to strike a balance between design and construction costs and the damaging consequences due to failures.